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UTILIZING GEOGRAPHIC INFORMATION SYSTEMS TO RECORD AND ANALYZE OSTEOARTHRITIS DATA IN JOINTS OF THE ARM: A METHODOLOGY FOR DRY BONES

by

ADAM J. BIERNASKI
B.A. University of Central Florida, 2015

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Arts
in the Department of Anthropology
in the College of Sciences
at the University of Central Florida
Orlando, Florida

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ABSTRACT

Osteoarthritis is one of the most common pathologies encountered in dry bone contexts. However, even with the wealth of publications on documenting the presence of OA from skeletons, these studies prove to be largely incomparable due to different scoring methodologies and procedures in calculating prevalence. The standardization of a new OA data collection procedure would mitigate variability in evaluating, scoring, and calculating the prevalence of OA, thus allowing accurate comparison between studies. However, this level of data collection has often been described as unwieldy and lacking concordance. This research outlines a new methodology that utilizes Geographic Information Systems (GIS) to record OA characteristics, levels of expression, and spatial arrangement on the articular surfaces of the arm. The data was then processed using the analysis and visual rendering capabilities of GIS providing examples of OA patterning on the articular surface, within the joint, and within the individual. Using this method, large standardized OA datasets can be stored and the patterns within them modeled through the use of digitization, composite raster overlays, and modified binning techniques. The patterns recorded by this analysis can offer a more robust dataset on OA occurring within the arm that can provide the ability to explore OA progression and its relationship with biomechanical factors in larger datasets.

To Dad, who took me to all the museums.

To Andrea, Melanie, Courtney, and Aurelia.
Do amazing things.

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Above all else, I would like to thank my committee members:

Thank you to Dr. Schultz for the idea behind this topic and your innate ability to happily throw me into the deep water and patiently wait for me to find my way out. For this experience, I am grateful.

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LIST OF ABBREVIATIONS

DRUJ	Distal Radioulnar Joint
DSLR	Digital Single Lens Reflex
GIS	Geographic Information Systems
KL	Kellgren-Lawrence
NAGRPA	Native American Graves Protection and Repatriation Act
OA	Osteoarthritis
PRUJ	Proximal Radioulnar Joint
SQL	Structured Query Language

I: INTRODUCTION

The word *methodology* in a scientific framework can embody multiple meanings. It can refer to the means by which a researcher initially gathers data, the technique of manipulating and testing this data, or it can be the mode through which a researcher determines a classification for the data. Each of the preceding can either be achieved in isolation or, like many research projects, stacked together for maximum interpretation. The use of methodologies carries considerable weight in the advancement of knowledge in the scientific community. Without defined means in which to gather, classify, and test data, there would be no results to discuss or breakthroughs to be made. From Libby's (1961) development of radiocarbon dating to Longin's (1971) method of collagen extraction, it can arguably be stated that the development and adaptation of new methodologies propels the advancement of the anthropological community though obtaining and organizing knowledge once thought unobtainable. Many of these methods have been tested, improved over time, and remain solidly standardized, while others remain debated and situationally specific.

In the field of paleopathology, the dependence on methodology is equally important as in other disciplines. Ortner (1991) places methodology as step two in a six-overlapping-stage system – situated immediately after defining the area of scientific interest (Figure 1). Stage two is described as the "creation of a methodology for conducting research on the subject" (Ortner, 1991, p. 5). All steps that follow are affected by the quality of this methodology including the accumulation of a body of descriptive data, development of a classification system, hypothesizing on observed phenomena, and comparing this research to other research throughout disciplines (Ortner, 1991). If Ortner is correct in his assessment, then methodologies should exist to ensure each additional step is accomplished, yet this has proven to be problematic due to issues of rigor within the discipline.

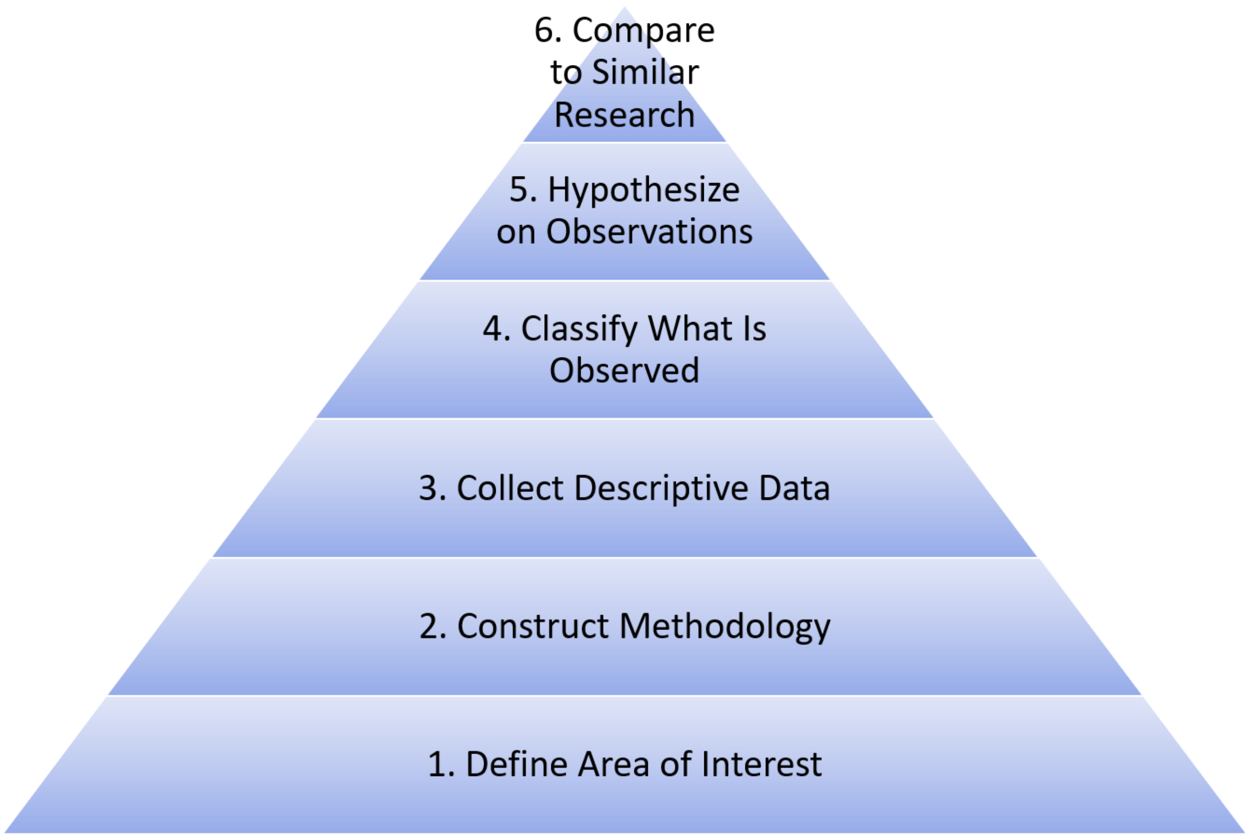


Figure 1: Ortner's (1991) stages of development for paleopathological research. Each step can be stand alone or overlap the next but is dependent on the function of the previous.

In her centennial perspective on the state of paleopathology, Grauer (2018) lays bare a century long history of rigor issues, including data collection, citing what Jarcho (1966) attributed to weak methodologies and lack of standardization in collection methods. While she explains the responses to Jarcho's assessment was met with suggestions and published compendia that assist with diagnosis (Grauer, 2018, p. 909), researchers may want to consider if a diagnosis of dry bone pathology truly assists in correcting disorganized data collection or does it merely place a label over unsystematically collected data. It is a cyclical argument, yet the interrelationship between dry bone diagnosis and data collection is veritably unquestionable as the characteristics through which the diagnosis is reached often becomes the focus of the data collection.

Central to this debate within paleopathology is osteoarthritis (OA). Because it is one of the most common pathological conditions in ancient and modern populations (Ortner, 2003), the understanding of the etiology, pathogenesis, and progression of this pathology through the evaluation of dry bone holds both paleopathological and clinical significance. Buikstra and Ubelaker (1994) attempted to standardize OA data collection methods in the interest of comparison and data retention in the event of repatriation. However, soon after, this attempt became mired in debates over the significance of OA characteristics useful in its diagnosis (refer to Rogers and Waldron, 1995; Rothschild, 1997; Weiss and Jurmain, 2007). As a result, researchers have had their choice of method for dry bone diagnosis of OA and with it, the type of data collected. Based on Ortner's (1991) steps, this failure in creating a uniform body of descriptive OA data also prevents the ability to classify, hypothesize, compare, and basically understand the pathology.

To circumnavigate this issue with data collection arising from diagnosis and to move toward a method of OA data collection which is standardized, this research agrees with Bridges (1993) in that by providing the most complete and unmanipulated data possible, it will facilitate comparison and has the best potential to advance the understanding of the OA pathology. This would entail data collection for all characteristics of OA (e.g., lipping, porosity, and eburnation) regardless of the debate of their significance in diagnosis. It is a distinct possibility that a wide body of OA data may support or refute certain characteristics' place in dry bone OA diagnosis.

Initiating the collection of this data in the past has proven unwieldy and difficult to interpret, favoring instead the use of vague averages of OA involvement on articular surfaces (Bridges, 1993). However, since the early 1990s, technological advancements in digital imaging and recording software have progressed to the extent where collection, recording, and analysis of dry bone OA need not be complicated. Geographic Information Systems (GIS) have not only demonstrated the capability for the retention of a wide range of datasets, but also offers the opportunity to mitigate interpretation and replicability issues that may be caused by inter-observer variation (refer to Waldron and Rogers, 1991).

Considering the place of methodology and robust data collection in the paleopathology hierarchy proposed by Ortner (1991) and building upon the idea of standardization set forth by Bridges (1993) and Buikstra and Ubelaker (1994), this methodology considers what a twenty-five year advancement in technology may offer in the collection and analysis of raw OA data. It is the purpose of this work to outline a standardized data collection procedure and propose analysis methodology where robust datasets of dry bone OA characteristics are created and analyzed in GIS. Doing so would provide not only a broad dataset to ensure comparability but also a more comprehensive pattern analysis than what may be provided through traditional aspatial means (refer to Chapman and Stewart, 2014; Fojas et al., 2015). Using OA characteristics and data collection protocols outlined in Buikstra and Ubelaker (1994), this methodology would initiate the creation of a standardized datasets containing OA characteristics and positions. It is the hope that through the implementation of this methodology and the data it compiles, a better understanding of the diagnosis and progression of OA can be achieved through robust data collection, spatial analysis, and comparability through standardization.

Based on GIS and cartographic techniques explored by Chapman and Stewart (2014), Fojas et al. (2015), and Merbs (1983), this method employs the digitization of dry bone OA characteristics from photographs of the articular surfaces of the arm. Through use of the software's capabilities for rendering and manipulating large quantities of data both statistically and visually, it is anticipated that patterns of progression and areas prone to higher severity can be rendered with greater efficiency than traditional analog means. The resulting high-resolution data can then be analyzed and hypothesized according to the progression described by Ortner (1991). The main objectives of this research concern the following:

- Utilize GIS to develop a methodology which would outline how to collect, input, and analyze data of dry bone OA from photographs of articular surfaces.
- Apply this method to the articular surfaces of the glenohumeral joint, elbow, distal radioulnar joint (DRUJ), and the radiocarpal joint.
- Demonstrate the analysis capabilities of this method in both realistic and modeled examples focusing on the recording, development, and progression of OA pathology within joints, the individual, and within a population sample.

II: LITERATURE REVIEW

The amount of literature that exists on the pathology known as osteoarthritis is varied and exhaustive. For the purposes of a comprehensive review, relevant elements of both clinical and dry bone contexts will be offered. Due to the perceived unchanging nature of the disease, dry bone (archaeological) contexts provide a unique opportunity to view the outcome of the disease short of utilizing macerated cadavers in clinical studies. OA is a pathology of the synovial joint, this includes elements of soft tissue and hyaline cartilage that act as a single organ (or failure of an organ) and OA in dry bone contexts are merely a result of this organ failure. Following a brief introduction to the pathology and a review of the literature concerning clinical and dry bone OA, a brief review of biomechanics of the arm will be presented. Because movement of the human body continues throughout the progression of OA, biomechanical stresses can become relevant in the data analysis phase.

Osteoarthritis

In its most simplistic definition, osteoarthritis represents the body's attempt to repair the failure of a synovial joint (Arden and Nevitt, 2006). This can lead to a variety of joint responses in both living tissue and dry bone. The history of OA extends from the fossil record, through preindustrial humans and well into modern populations (Jurmain and Kilgore, 1995; Ortner, 2003). It is one of the main contributors to archaeological bone pathology as well as one of the most chronic disorders in the world (Kapoor, 2015; Rogers and Waldron, 1995; Waldron, 2012). Due to this extensive chronology and its effect on modern population, a considerable amount of clinical and paleopathological literature has been devoted to understanding its pathogenesis, aetiology, and epidemiology. While OA comparisons between living and dead populations can be problematic (Rogers and Waldron, 1995; Waldron, 2012), clinical literature has contributed considerably to understanding the aetiology of OA prior to the resulting long term skeletal changes manifest in archaeological contexts (Weiss and Jurmain, 2007).

Any pathology that manifests within the archaeological record initially affected living tissue. The rate of onset, tissue of origin, and length of survival with a chronic condition or injury has the capability of affecting a degree of response from the skeletal system (Roberts and Manchester, 2010). Since the pathological 'life-span' initiates within living tissue, the opportunities, if available, to examine it clinically should not be overlooked. In the case of OA, where pathological characteristics have remained relatively unchanged for over 100 million years (Dequeker and Luyten, 2008), this consistency provides continuity between clinical findings and archaeological contexts. It is this interplay between clinical and archaeological research that contributes to a holistic picture of OA. As a result, both are synthesized here.

Clinical Osteoarthritis

Clinical OA is defined as a pathology of multiple aetiologies but with similar biological, morphological, and clinical outcomes affecting synovial joints (Brandt, Dieppe, and Radin, 2008; Cooper, Javaid, and Arden, 2014). This can include a wide variety of pathological changes manifesting as joint pain with synovitis and articular cartilage loss with subchondral bone modification (Felson, 2004; Reginster, 2014). While almost all definitions of OA emphasize the loss of articular cartilage, Brandt, Dieppe, and Radin (2009) emphasize that the best way to describe OA is as a repair, or failed repair, of damage caused by mechanical stress on joint tissues. This definition acknowledges many causes that can compromise the joint tissues while recognizing one common end stage – joint modification through repair (Radin et al., 1991). This idea echoes Dieppe (1990) a year earlier who described OA not as a disease, but as an abnormal state of a synovial joint brought about my multiple factors each triggering a reaction pattern leading to OA.

Clinical Epidemiology, Prevalence, and Affected Joints

Due to the excessive prevalence of OA in modern society, the explorations into its risk factors and aetiology have become increasingly important in mitigating the financial and public health issues arising from it (Cooper et al., 2014). As a result, modern research has extensive, dynamic, and often contradictory data relating to those at risk and the joints most affected. In the United States, there is a strong link of OA prevalence to increased age with an estimated 78.4 million diagnosed cases expected by 2040 (Hootman, Helmick, Barbour, Theis, and Boring, 2016; United States Centers for Disease Control and Prevention, 2018). Radiological diagnosis can be confirmed in adults around 45 years or older, with the most common joints being the cervical and lumbar spine, distal interphalangeal joints, knee, and hip (van Saase, van Romunde, Cats, Vandenbroucke, and Valkenburg, 1989). This study by van Saase et al. (1989) also revealed differences between populations of various regions for age of onset, joints affected by sex, and level of involvement. All of which can be attributed to one or a combination of variables affecting the susceptibility of OA. These include genetic predilection, diabetes, body mass, and biomechanical influences (Hooper, Holderbaum, and Moskowitz, 2005; van Saase et al., 1989; Weiss, 2006; Weiss and Jurmain, 2007). The study concluded with the observation that joints with a low prevalence of OA in one population is similarly reflected in all populations and likewise, frequently affected joints show the same. Therefore, it is most likely that “the aetiology of most osteoarthritis is the same in all populations” (van Saase et al., 1989, p. 279).

With the exception of the wrist (von Schroeder and McCabe, 2015), glenohumeral and elbow OA are relatively uncommon in modern populations and do not typically occur without external stress or senescence (Dalal, Bull, and Stanley, 2007; Doherty and Preston, 1989; Roberts and Manchester, 2010). Support for OA's relationship to external stress are numerous (refer to Jurmain, 1999, pp. 82-83). Many studies show positive association between high stress repetitive motion or vibration with OA in occupational/sports related activities including pneumatic tool workers (Bovenzi, Petronio, and Di Marino, 1980; Resnick and Niwayama, 1988), foundry workers (Mintz and Fraga, 1973), and weight lifters (Fitzgerald and McLatchie, 1980).

Osteoarthritis Subset Synthesis

Early clinical and current archaeological literature focuses on a multicausal aetiology for OA which divides it into two classifications: idiopathic (primary), and secondary. Idiopathic, is caused by various factors including age, sex, genetic predisposition, hormones, and mechanical stress, while secondary is the result of trauma or infection (Ortner, 2003; Waldron, 2012; White, Black, and Folkens, 2012). Clinical literature acknowledges many causes that will contribute to the susceptibility for OA (Cooper et al., 2014), however more recent interpretations eliminates the idea of idiopathic OA in favor of the interpretation that all OA is secondary (Brandt et al., 2009). This interpretation emphasizes OA as a healthy prolific response to a mechanical problem and therefore contradicting its past classification as a degenerative disease (Brandt et al., 2008, 2009; Nuki and Salter, 2007).

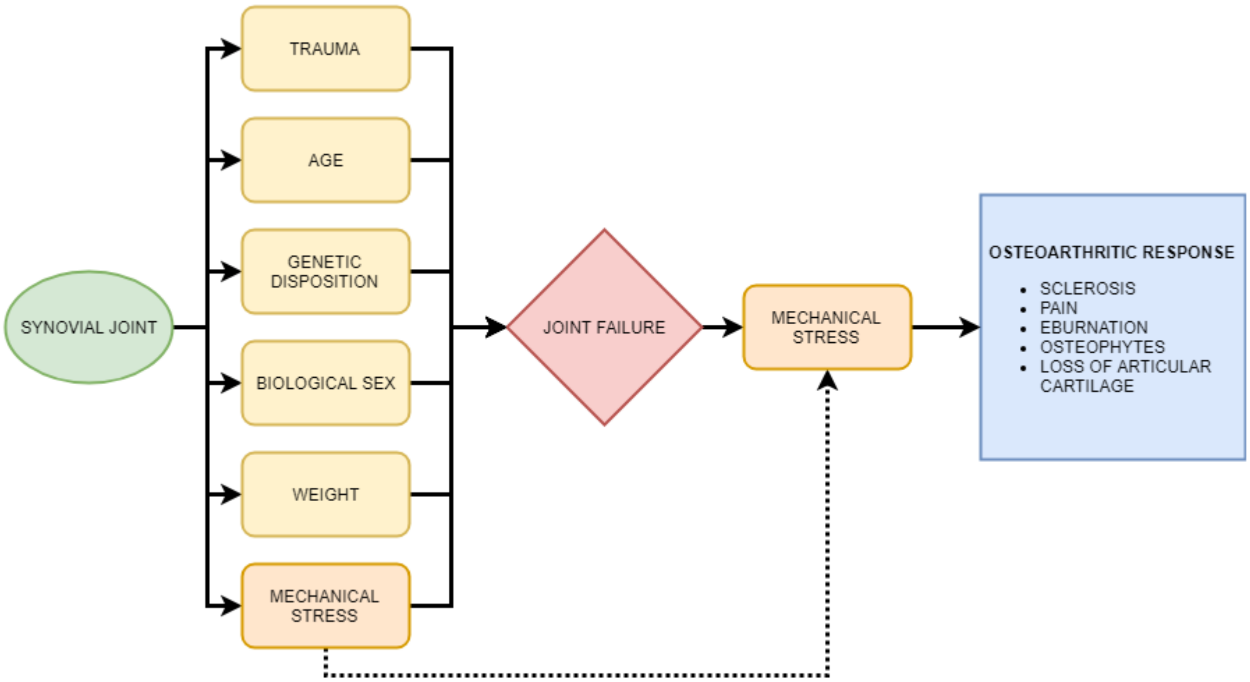


Figure 2: Clinical OA interpretation in which all OA is secondary and not linked directly to a specific aetiology (based on: Brandt et al., 2008; Brandt et al., 2009; Cooper et al., 2014; Ortner, 2003; White et al., 2012).

Regardless of the systemic risk factors involved, the mere function of the synovial joint system implies that mechanical stress is likely to be involved in the evolution and pathogenesis of all OA occurrences after the failure of the joint (Nuki and Salter, 2007) (Figure 2).The body's mechanisms for repairing damaged tissues prove inadequate for maintaining homeostasis within the joint and, as a result, the body attempts to compensate for additional loading stress though remodeling (Brandt et al., 2008). Brandt et al. (2009) argues that the normalization of these loading stresses has been shown to reduce or eliminate OA development in human proxies through immobilization. Those not immobilized can expect to exhibit increased osteophytic and sclerotic development (Brandt et al., 1991; Dedrick et al., 1993; Palmoski and Brandt, 1982).

Clinical Presentation

The clinical indication for OA often relies on the onset of pain. By the time pain is detected, a significant biochemical transformation is underway in an attempt to mitigate mechanical stress and restore homeostasis of the joint. According to Felson (2004), injured cartilage increases the production of a molecule known as aggrecan. The repulsion of this negatively charged molecule by the collagen II chains within the hyaline cartilage is what give the cartilage its compressive stiffness. If the degradation of aggrecan outweighs its synthesis, the negative charge of the matrix will attract water molecules leading to cartilage swelling. If no preventive measures are undertaken, then the imbalance between synthesis and degradation will cause less functional collagen I production cascading into a deficit in cartilage matrix production leading to fibrillation and cartilage loss (Felson, 2004). It is important to note that these early changes are often undetected as articular cartilage is aneural and will not register symptomatic indications of OA (Rannou, 2014).

At this phase of progression, OA shifts from a symptomatic pathology to a structural one as modifications become radiologically (and archaeologically) apparent (Felson, 2004). It is not readily obvious if the modifications to the subchondral bone area are a cause or a product of cartilage loss, yet model evidence suggests that changes in mineral density of the subchondral bone precede the cartilage damage and adversely affect the biomechanical environment of the overlying cartilage (Buckland-Wright, 2004; Martel-Pelletier, Lajeunesse, Reboul, and Pelletier, 2007; Radin and Rose, 1986). This subchondral remodeling is not a singular occurrence, but has early and late phases starting with porosity and thinning of the subchondral plate before resolving to sclerotic thickening and calcification of the cartilage layer (Rannou, 2014).

However, prior to the subchondral thickening, the existence of osteophytes will often become radiologically apparent. Osteophytes are defined as hypertrophic chondrocytes usually within the periosteum on the cartilage-bone border that have undergone endochondral ossification (van der Kraan and van den Berg, 2007). Buckland-Wright (2004) has observed that osteophyte formation occurs many months before the narrowing of the joint space through articular cartilage loss. Sclerosis, joint space loss, osteophyte formation, and the addition of bone cysts, which appear at the focal points of severe cartilage damage within the subchondral bone, are all radiologically recognizable landmarks for OA and the basis for clinical radiological assessment (Goldring, 2009; Kellgren and Lawrence, 1957).

Clinical Assessment

One could offer a strong argument that the physical manifestations of OA are easier to observe in archaeological contexts. Viewing of the articular surface offers an unfettered view of the surface of the subchondral bone without the obstruction of living tissue. Unfortunately, the limitations in viewing OA within living tissue have been constrained by the technologies of the time. In 1957, Kellgren and Lawrence published a method for assessing OA through x-ray which was the most advanced non-invasive procedure of the day. It has since become the de facto standard for the radiological assessment of OA known as Kellgren-Lawrence (KL) grades (Blanco, 2014; Cooper et al., 2014). Features considered for a radiological differential were the formation of osteophytes, sclerotic subchondral cysts, altered shape of the epiphyses, narrowing of the joint space due to cartilage loss, and periarticular ossicles of the interphalangeal joints (Blanco, 2014; Kellgren and Lawrence, 1957). The development of any combination of these factors are graded on a scale of zero (absence of radiographically observable changes) through four (severe) in the opinion of the observer.

While the clinical diagnosis and understanding of OA serves the contemporary purpose for overall wellness and disease management, understanding the patterns of OA affecting populations in the past offers a paleopathological history for the epidemiology of OA and possible direction in the future. If modern clinical information is a logical starting point for understanding a pathology that has not changed considerably in its presentation for over a million years, then we should be able to assume the following in ancient populations:

- The aetiology will remain unknown as it is not fully comprehended in clinical literature beyond many interrelated and/or unrelated factors.
- All OA is secondary. Continued stress and movement after the failure of the joint might be reflected in the response of the joint to repair or compensate for this regardless of the aetiology (Figure 2).
- OA of the arm is less common than in other body weight bearing joints and is influenced more by mechanical stress, trauma, and senescence.

Regardless of the causes that to lead joint failure, the chronic nature of OA and continued movement of the elements effected may provide unique patterns relating to the progression of the pathology and the related biomechanical stresses of the affected individual. The survivability of bone in archaeological contexts provides a remarkable opportunity to create a descriptive dataset of OA where these patterns might be assessed.

Dry Bone Osteoarthritis

Second only to dental disease, OA is the most common pathology found in archaeological contexts (Ortner, 2003; Rogers and Waldron, 1995). Often referred to as degenerative joint disease, this nomenclature is better served in clinical contexts where the joint as an organ degenerates, yet initiates osseous changes which are, ironically, prolific. This osseous remodeling is proliferative in that it exhibits osteoblastic activity through sclerotic development in the subchondral bone as well as osteophyte formation rather than erosion (Waldron, 2012). The prevalence of OA in archaeological populations is difficult to ascertain and must be inferred from clinical data (Waldron, 2012), however archaeological collections allow for epidemiological comparisons between groups and expansion of the range of epidemiological data (Jurmain and Kilgore, 1995).

Much like clinical OA, the widespread proliferation of OA in archaeological contexts may have roots in any one or combination of many aetiological factors such as genetic disposition, sex, obesity, age, trauma, and activity (Jurmain, 1977; Rogers and Waldron, 1995; Weiss, 2006; Weiss and Jurmain, 2007). Similar to clinical literature, a distinction between OA types in dry bone is recognized which separates it into idiopathic, which occurs without a definitive cause, and secondary, when a cause such as trauma or disease is known (Jurmain, 1999). The realization that any of these causes may overlap to bring about joint failure makes ascertaining the exact aetiology problematic and has stood as an argument against over-simplified direct interpretations of activity (Bridges, 1992). This argument against interpretations of activity loses much of its credence when all OA is considered as secondary.

Dry Bone Presentation and Differential

Osteoarthritis in dry bone has three primary characteristics, one that is clinically diagnostic on the joint surface through x-rays: marginal osteophytes or lipping, and two that are best observed in dry bone contexts or macerated cadavers: eburnation and porosity (Rogers and Waldron, 1995; Waldron, 2012). Subchondral pitting or porosity and osteophytes have been addressed in the clinical literature section as a subchondral reaction to the loss of articular cartilage and the endochondral ossification of chondrocytes along the margins of the periosteum and perichondrium (van der Kraan and van den Berg, 2007). Eburnation is often hailed as the definitive indicator of OA where contact points between the articulating bones create a polished surface on the subchondral bone parallel to the line of motion (Klaus, Larsen, and Tam, 2009). If eburnation is not present Rogers and Waldron (1995) recommend it should be diagnosed with two of the following: marginal osteophytes, new bone on joint surface, pitting on the surface, or alteration to the joint architecture.

All of these characteristics are widely mentioned in diagnosis of OA in dry bone; however, there is considerable debate in the significance of each which often leads to variation in the data collected. Weiss and Jurmain (2007) emphasize, like Rogers and Waldron (1995), that eburnation is the definitive indicator for severe OA involvement. Yet, they also allude to a correlation between biological age and osteophyte development which would impede osteophyte significance in diagnosis (Weiss and Jurmain, 2007). Similarly, Rothschild (1997) questions the diagnostic significance of porosity and indicates eburnation, while diagnostic, serves more as an indication of severity. Therefore, what is diagnostic of severe OA and what might be an early indicator of OA could be hidden in different configurations of these characteristics.

The characteristics of OA may be mono-articular or poly-articular and any synovial joint has the potential risk of being affected (Ortner, 2003; Waldron, 2012). Typically, it is a combination of the spatial distribution of affected joints and the presence of the osseous characteristics of OA that contributes to the diagnosis of OA in dry bone. Unlike other degenerative joint diseases, osteoarthritis is proliferative and therefore deposition of new bone, sclerosis (in radiographs), and osteophytes are characteristics. Gout, rheumatoid arthritis, ankylosing spondylitis, and psoriatic arthropathies are classified as erosive joint diseases, which includes cortical destruction and sharp or scalloped ridges characteristic of osteoclastic activity (Waldron, 2012). Presence of this would preclude the diagnosis of OA (Table 1).

Table 1: Differential characteristics of erosive and prolific arthropathies (derived from: Rogers and Waldron, 1995; Waldron, 2012)

Pathology	Erosive	Prolific	Differential Characteristics
Osteoarthritis		X	*Not often bilateral. Affects cervical, lumbar, knee, hip, elbow, interphalangeal joints. Could be any synovial or apophyseal joint.*
Rheumatoid Arthritis	X		*Bilateral. Affects distal foot phalanx, hands, knee, ankle, neck.*
Diffuse Idiopathic Skeletal Hyperostosis	X		*Ossification of ligaments and insertions of the spine. Facet joints not affected,*
Ankylosing Spondylitis	X		*Bilateral. Sacroiliac joints moving superior with the ossification of annulus fibroses.*
Psoriatic Arthropathy	X	X	*Often companion of psoriasis. Distal interphalangeal joints (cup – pencil) occasionally prolific, joints of the upper limb. Many variations difficult to diagnose.*
Gout	X		*First metatarsophalangeal. Oval lesions in long axis of affected bone.*

Osteoarthritis of the Arm in Archaeology

Osteoarthritis of the upper appendicular joints are of unique interest to bioarchaeologists. The arm is not a weight bearing limb and is predominantly used for manipulation of the environment in a way that is culturally normative for the individual. Unlike the body weight bearing joints of the hip, knee, and back, OA in arm joints is uncommon and rarely seen outside senescence or injury (Doherty and Preston, 1989; Resnick and Niwayama, 1988). In clinical studies prevalence within the elbow has been found to be 1.3% - 7% (Dalal et al., 2007). In ancient populations, OA of the arm has been found in greater frequency (Ortner, 1968, 2003). Jurmain (1980) found the elbow to be the most asymmetrical appendicular joint of the body for the development of OA and subject to a greater influence by occupational stress. If modern population's OA focuses more on body weight bearing joints of the hip and knee and age related arthropathies in the arm, then it is not illogical to conceive that a comparatively younger ancient population's prevalence for arm OA is not widely influenced by obesity nor extreme old age. With the removal of these variables, the reliance on the biomechanical stresses has led to an extensive range of publication on the interpretation of activity in archaeological populations based on variables such as handedness, gendered divisions of labor, and unique cultural practices (Angel, 1966; Jurmain, 1999; Merbs, 1983; Ortner, 1968).

Patterns of Activity

The concept of activity-induced pathology began in the mid-1960s through a singular interpretation by J. Lawrence Angel (1966) relating the prevalence of elbow OA to the cultural activity of throwing the atlatl. Angel also noted a difference in elbow OA prevalence along the lines of biological sex, associating marginal lipping in female arms to seed grinding (Angel, 1966). From this launching point, Ortner refined the progression of degeneration in the elbow referring to it as a “degenerative change profile” (1968, p. 146) and lauded its ability to reconstruct patterns of body use. Due to the overwhelming enthusiasm in the possibility to anticipate action within ancient populations, it took only two years for the term “atlatl elbow” to become sustainable enough to be quoted in publication as synonymous for OA within the radiohumeral joint. While this trend picked up speed throughout the 1970s through the efforts of Jurmain and others (for a comprehensive list refer to Jurmain, 1999), it was Merbs’s 1983 Sadlermiut Inuit study that illustrated the extremely wide context needed to merely suggest a motion or activity. Merb’s 1983 publication of his 1969 doctoral dissertation took into account the overall patterning of OA within the joint much like Angel (1966) and Ortner (1968), but associated ethnographic accounts to reinforce his interpretation of movement.

In the 1990s, there was continued publication on the subject of activity-induced pathology that placed it within a larger context that explored links of subsistence and differences in activity by gender (Larsen, 1995; Weiss and Jurmain, 2007). However, as the concept broadened, so did the scrutiny of the methods, conclusions, and the means of analysis (Bridges, 1992). A new focus on complexity highlighted the improbability that a pathology with such an intricate aetiopathogenesis could definitively be tied to a single cause such as activity (Jurmain, Cardoso, Henderson, and Villotte, 2012; Jurmain, 1999; Weiss and Jurmain, 2007). Since the 1990s, academia has exhibited a noticeable drop in publication focusing on OA in relation to activity due to a questionable aetiology which would require broad speculation on the part of the researcher (Weiss and Jurmain, 2007). Weiss and Jurmain (2007) regret this reduction in OA research as it assisted in understanding the skeletal patterning and possible progression of OA. However, through methodological adjustments such as recording specific variables noted for variations in OA prevalence like age and sex, researchers continue to utilize a multidisciplinary approach with OA to interpret activity in ancient populations including historical information (Austin, 2017), and musculoskeletal stress markers (Schrader, 2012).

Merbs's (1983) initial study using traced overlays of OA patterns within the Sadlermiut population not only showed possible differences in prevalence of OA by sex, but it illustrated a division of labor, and correlated cultural activities to ethnographic accounts. Weiss and Jurmain (2007) argue that OA patterning, both within the body and in populations, are important to interpreting the pathology itself (438). Yet, many studies focus on the interpretation of activity or merely mention the pathology in passing. Due to the complex aetiology of OA, many of these accounts of activity are seen as gross speculation if an action is interpreted as the singular cause of OA development (Jurmain et al., 2012) (Figure 3). However, much like the argument for OA equating directly to activity, the argument against activity interpretation fails to consider the secondary nature of OA where a biomechanical component affects the joint *after* the joint has failed from any and all aetiological causes (Brandt et al., 2009). This circumnavigates the issue of aetiology and allows OA interpretation from the point of continued movement after joint failure – not as a direct causality (Figure 4). These interpretations would be especially noteworthy in cases of eburnation. If these limitations are considered, and if context is available, patterns of motion might be inferred after the failure of the joint.

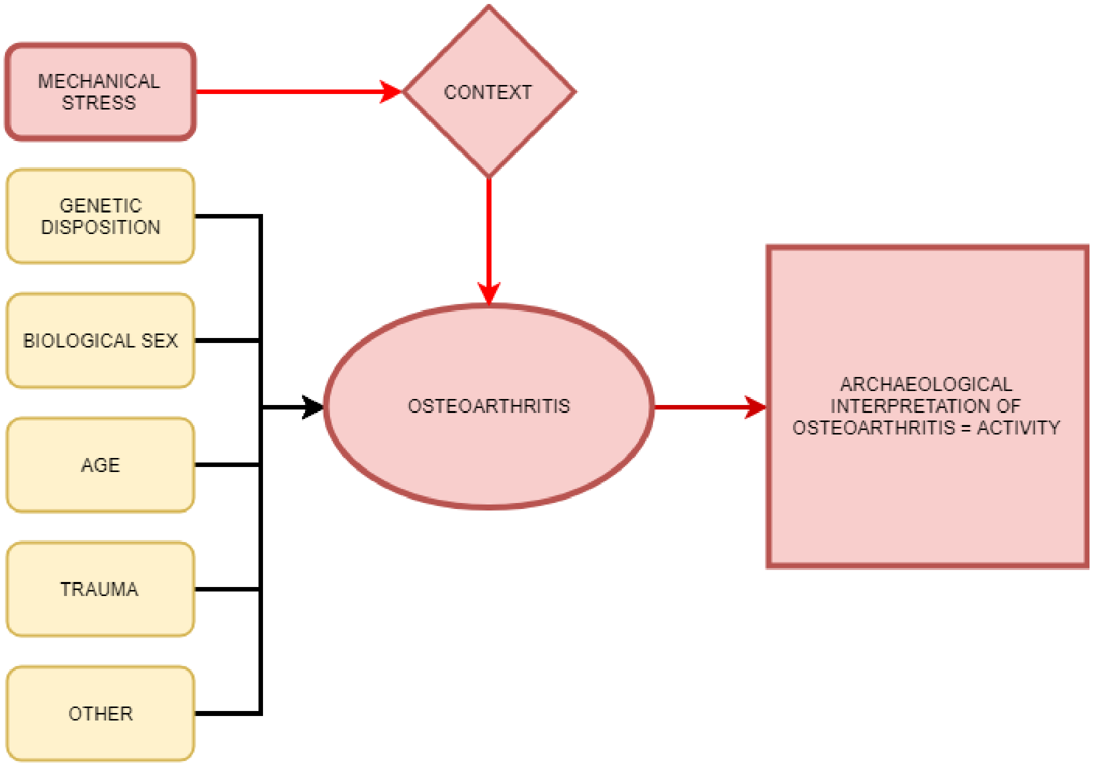


Figure 3: Example of erroneously interpreting activity from OA patterns by omitting other aetiological factors.

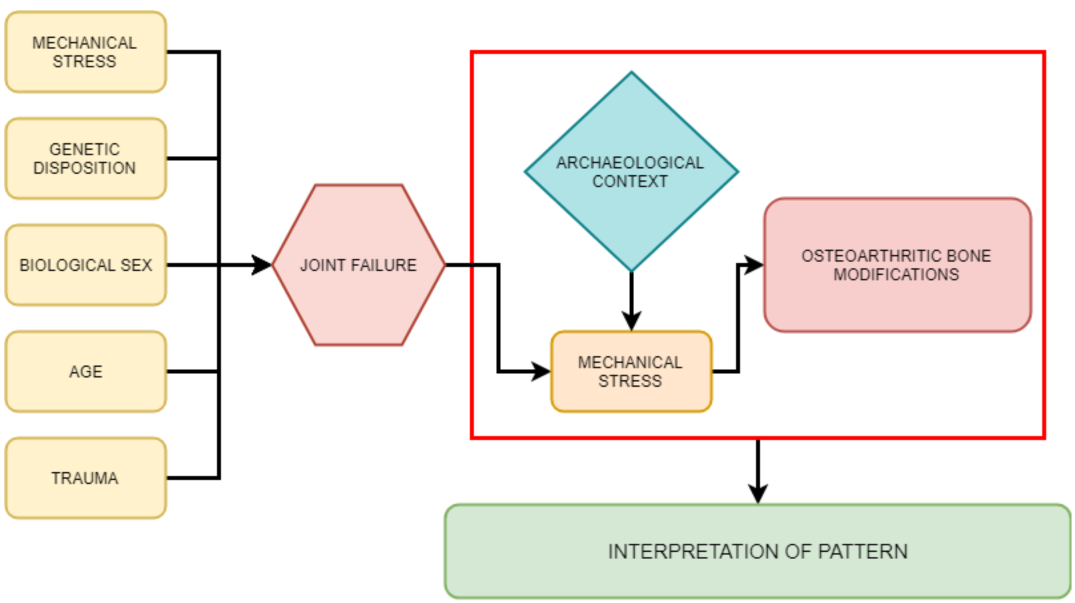


Figure 4: Interpretation of OA patterns as a product of secondary response after joint failure incorporating all aspects of the aetiology. The red box indicates the limits of OA interpretation within archaeological contexts.

Dry Bone Collection Issues

In 1990, the passage of the Native American Graves Protection and Repatriation Act (NAGPRA) signified a victory for the descendants of Native American Peoples in reclaiming the once curated remains of their ancestors, yet also raised concerns about a significant loss of data within many fields (Buikstra and Ubelaker, 1994; Rose, Green, and Green, 1996). In response to this impending loss of data, anthropologists began focusing on ways to standardize skeletal data collection protocols in order to gain the maximum amount of comparable data from remains that might be repatriated in the future. As a result of these efforts, in 1994 Buikstra and Ubelaker published *Standards for Data Collection from Human Skeletal Remains*, which has become the standard for archaeological data collection. The volume covers basic collection, measurements, and pathological assessment – including OA.

Due to the need for comparable data in light of a variety of diagnostic methods, Buikstra and Ubelaker (1994) ask the researcher to collect a broad range of OA characteristics, expressions, and generalized spatial locations on the articular surface. The observer is asked to determine the extent of the joint surface affected by eburnation, porosity, or marginal lipping and record the degree of expression. The extent of joint surface affected by each is recorded as a fraction divided into thirds. These procedures are by no means comprehensive and the authors encourage methodological adjustments to be made allotting for time and the research question being investigated (Buikstra and Ubelaker, 1994).

While the intent for standardization shows concern that was voiced by Bridges (1993) a year earlier, the OA data collection procedure in Buikstra and Ubelaker (1994) exhibits a few issues. Firstly, unless the bones are physically available, photographed, or drawn, the data will lack spatial context. Recording that a humeral head exhibits lipping on greater than two-thirds of its circumference is a method adequate for drawing general conclusions or aggregation data but inadequate for more nuanced determinations or pattern recognition. It does not an answer the question of which two-thirds were involved. Hypothetically, if a left glenoid was recorded as having lipping on greater than one-third of the margin, then any one of the following patterns would be correct (Figure 5). Secondly, while the creation of Buikstra and Ubelaker (1994) sought to standardize the data collection procedure, it did so emphasizing the need for replicability. Accurate replicability requires the ability to not only reproduce another individual's work, but to also offer a critique of the original pathological assessment. If there is a visual record delineating specific areas of OA involvement, then this is possible. If there is not, then the reliance on the skill and method of the original assessor to determine grade, type, and extent of OA manifestation is greater and reevaluation is not possible.

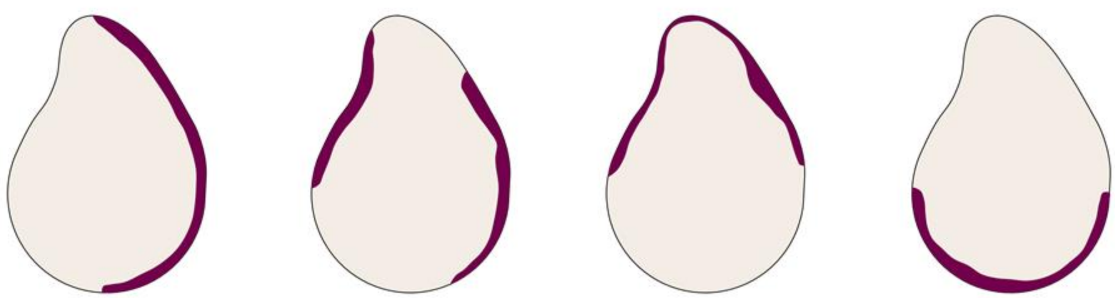


Figure 5: Hypothetical variations of the left glenoid exhibiting greater than one-third marginal lipping involvement.

The three main characteristics of eburnation, porosity, and marginal lipping included in the diagnosis of OA have been widely debated resulting in a variety of opinions on the relevance of data collected in dry bone contexts. Buikstra and Ubelaker (1994) choose to focus on data collection over diagnosis with more detailed collection of all characteristics, severity expressions, and percentage of location on the articular surface. Rogers and Waldron (1995) and Waldron (2009) choose to focus on the diagnostic aspect, citing eburnation as the definitive diagnostic criteria but accepting two of the following: lipping, remodeling, osteophytes, or porosity. In contrast to Buikstra and Ubelaker (1994), he cautions the use of ratings scales, citing the lack of concordance between studies (Rogers and Waldron, 1995). Still, other researchers find fault in using porosity and osteophyte development based on Rothschild (1997) and Weiss and Jurmain (2007) respectively (refer to Molnar, Ahlstrom, and Leden, 2011). The resulting variety in evaluating, scoring, and calculating the prevalence of OA has contributed to the difficulties in making comparisons between studies and formulating a wide body of data that can be compiled from many studies (Table 2).

A level of flexibility to shape data collection to the limits of research questions is understandable. However, the ambiguity of what data is collected and the multiple available resources a researcher may use often conflicts with the ideas behind standardization in which the researcher provides a means through which direct comparison between populations can be facilitated with greater accuracy. Watkins (2012) uses a modified Buikstra and Ubelaker (1994) data collection method to evaluate and to record OA data of the W. Montague Cobb skeletal collection. While slightly modified to accommodate for additional concerns within the scope of the research, it is still easier to compare this data to another study which uses Buikstra and Ubelaker (1994) than it would be to a study utilizing Rogers, Waldron, Dieppe, and Watt (1987) or Rogers and Waldron (1995). Members of a population that have or indicate OA in the Watkin’s (2012) study, may not be included if the Rogers and Waldron (1995) method is utilized.

Table 2: Examples of OA studies of the appendicular skeleton showing differences in evaluation, scoring, and calculation of prevalence.

STUDY	METHOD USED	OA CHARACTERISTICS EVALUATED	OA CRITERIA USED TO CALCULATE FREQUENCY	OA EXPRESSION EVALUATED	NOTES
WALDRON (1991)	Rogers et al. (1987)	Eburnation, marginal osteophytes, pitting of the joint surface and/or alteration in the joint contour.	Eburnation and osteophytes must be present for diagnosis. If not, the presence of any other two characteristics.	Unknown.	None.
BAETSEN, BITTER, AND BRUINTJES (1997)	Rogers et al. (1987)	Eburnation, marginal osteophytes, pitting of the joint surface and/or alteration in the joint contour.	Eburnation and osteophytes must be present for diagnosis. If not, the presence of any other two characteristics.	Unknown.	None.
LIEVERSE, WEBER, BAZALIISKIY, GORIUNOVA, AND SAVEL'EV (2007)	Buikstra and Ubelaker (1994)	Lipping, porosity, eburnation.	Any one or combination of the characteristics. Affected individuals classified as outlined in (Larsen, Ruff, and Kelly, 1995)	Severity recorded according to method.	Lipping deemed "barely discernable" as outlined in Buikstra and Ubelaker (1994) was omitted as diagnostic if no other characteristics were present.
MOLNAR ET AL. (2011)	Based on: Rogers and Waldron (1995); Rothschild (1997), and Weiss and Jurmain (2007)	Eburnation	Eburnation	Not recorded. Present or absent only.	Indicated eburnation was only definitive diagnosis. Others were debated.

STUDY	METHOD USED	OA CHARACTERISTICS EVALUATED	OA CRITERIA USED TO CALCULATE FREQUENCY	OA EXPRESSION EVALUATED	NOTES
ENG (2016)	Rogers and Waldron (1995); Waldron (2009)	Eburnation, marginal osteophytes, new bone on surface, porosity, joint contour alteration.	Eburnation. If not present any other two characteristics.	Not recorded.	Severity scores not recorded according to Rogers and Waldron (1995, p. 21)
MANZON AND GUALDI-RUSSO (2016)	Appendicular: Rogers and Waldron (1995)	Eburnation, marginal osteophytes, new bone on surface, porosity, joint contour alteration.	Eburnation. If not present any other two characteristics.	Unknown.	Spinal OA utilized two other different methodologies.
PALMER, HOOGLAND, AND WATERS-RIST (2016)	Waldron (2009)	Eburnation, marginal osteophytes, new bone on surface, porosity, joint contour alteration.	Eburnation. If not present any other two characteristics.	Rated mild, moderate, or severe.	None.
ZHANG ET AL. (2017)	Rogers and Waldron (1995)	Eburnation, marginal osteophytes, new bone on surface, porosity, joint contour alteration.	Eburnation. If not present any other two characteristics.	Slight, moderate, and severe depending on type and number of characteristics involved	Rated as joint complexes according to Larsen et al. (1995).
QUADE AND BINDER (2018)	Rogers and Waldron (1995)	Eburnation, marginal osteophytes, new bone on surface, porosity, joint contour alteration.	Eburnation. If not present any other two characteristics.	Unknown.	None.

Rogers and Waldron (1995) may offer a more definitive diagnosis of OA with eburnation as the decisive indicator. However, eburnation has been defined as an indicator of extreme cases of OA (Rothschild, 1997). This creates a dichotomy in the need to understand the progression of a pathology by identifying and recording it, arguably, only in its advanced stages. The full scope of disease progression may entail minor involvement that is immediately ignored as OA. Because the development and progression of OA is so poorly understood, data and expression for all characteristics of the pathology may provide better understanding of the earlier stages, how it progresses, if it is a linear process, and improved diagnosis in dry bone contexts. With this consideration, Buikstra and Ubelaker (1994) may still offer a better data collection procedure. In the past, this level of data detail may seem excessive and open to interpretation between observers (Bridges, 1993; Rogers and Waldron, 1995), yet if newer technologies were available to make this possible, what might the data show?

Biomechanics of the Arm

Osteoarthritis is a chronic disease linked to the synovial joints of the body. As a result, the continued movement of the joint as the disease progresses provides a unique opportunity for biomechanical patterns to become involved in the progression. Because the arm is less likely to be influenced by body weight and more influenced by movements motivated by environmental manipulation, an understanding of the basic biomechanical motions of the arm can contribute to interpreting patterns arising within the joints. Joint movement patterns in anatomically modern Homo sapiens have remained relatively constant with the range of motion and contact points within the joint constrained by human anatomy. With this in mind, a review of the basic biomechanics of the main joints in the arm including the glenohumeral, elbow, and wrist is provided for reference.

Glenohumeral Joint

The proximal end of the arm articulates at the glenohumeral joint. This joint consists of the one-third spherical humeral head articulating within the pear-shaped elongated concavity of the glenoid fossa of the scapula. The shallowness of the glenoid allows for a wide range of motion and rotation of the shoulder but leaves it predisposed to dislocation (White et al., 2012). There is also significant morphological variation within the glenoid affecting the loading of the shoulders correlating to OA development patterns within the glenoid and humeral head (Walch, Badet, Boulahia, and Khoury, 1999). Contact within the glenohumeral joint is shown to be greater and more stable at mid-elevation positions rather than at the extremes of joint position (Itoi, Morrey, and An, 2009). The contact point moves inferiorly and anteriorly during internal rotation, posteriorly and inferiorly in external, and superiorly with elevation (Itoi et al., 2009; Kaufman and An, 2008; Soslowsky et al., 1992; Yamamoto et al., 2007).

Elbow

The elbow consists of the distal end of the humerus and the proximal ends of the radius and ulna. The elbow is a combination of three synovial articulations and these structures allow for two degrees of freedom in flexion and extension as well as pronation and supination. The joints of the elbow are the ulnohumeral joint consisting of the trochlea of the humerus and the trochlear notch of the ulna, the radiocapitellar joint consisting of the capitulum of the humerus and the radial head, and the proximal radioulnar joint (PRUJ) formed by the radial head and the radial notch of the proximal ulna (White et al., 2012).

According to Itoi et al. (2009), contact within the joint is a function of the joint and loading positions with the increased loading along the axis leading to increased lateral articular contact. While absorbing much of the stress in loading during flexion and extension, pressure within the ulnohumeral shows no definitive change during pronation and supination (Hwang et al., 2018). However, varus and valgus loading of the radioulnar joint will change these contact points (Itoi et al., 2009). Yet, there are varying degrees of pressure and contact of the radiocapitellar and radioulnar joints in the stabilization of the elbow during pronation and supination. Pronation engages and increases pressures within the radiocapitellar joint and supination the radioulnar joint (Hwang et al., 2018; Omori et al., 2016).

Wrist

The distal end of the radius articulates with the lunate (mesial) and scaphoid (lateral) and the distal articular circumference of the ulna articulates with the ulnar notch of the radius. While the involvement of the radiocarpal articulations may be a future consideration for this methodology, this work will focus on the pivot joint of the distal radioulnar joint (DRUJ). The DRUJ is integral to the motions of pronation and supination and, with 220˚ of the ulnar head incased in articular cartilage (Huang and Hanel, 2012), it is a candidate for being effected by OA of the wrist. Current biomechanical interpretation the DRUJ is that the ulna is a fixed position around which a specially adapted radius rotates. This rotation is related to the degree of flexion and extension of the elbow (Lees, 2013). Due to the relationship between the proximal and distal radial ends and the stresses acting upon them, there may be correlation in OA patterns between.

III: METHODOLOGY

Because elements of standardization are based on utility and ease of implementation, standard field equipment and software was used that would be available at most academic research institutions. It also utilized standard dry bone photography practices, i.e., bones were photographed in standard anatomical orientations. This was done to explore how this methodology might be applicable within the confines of traditional documentation methods which include remains that were photographed and then repatriated. The first step in this process is access to a dry bone, or archaeological, population sample to begin documentation. The sample utilized here was limited to the purpose of aiding in the creation of this methodology and demonstrating analysis examples. Conclusions as to what could be tentatively stated about this sample population are not within the scope of this research and will be left for future research considerations. The following sections outline the point of origin and selection of the sample, the criteria by which it was assessed for OA, the process of photography, and an overview of the GIS that was used to evaluate it.

Sample

The dry bone sample currently being used to develop this method originates from Dayr al-Barsha within the Al-Minya province of Upper Egypt (Figure 6). Situated on the east bank of the Nile at the mouth of the Wadi Nakhla, Dayr al-Barsha was predominantly used as the necropolis for the city of Hermopolis during the First Intermediate and Middle Kingdom periods but remains from the Predynastic through the Coptic era have been found (Brovarski et al., 1992). The area served as a major site for quarrying limestone during the Late Period and New Kingdom (Brovarski et al., 1992). This known quality makes this population of ideal interest in

OA study as the repetitive motions, vibrations, and heavy lifting involved with stonework may offer increased occurrences of OA in the arm joints.

Figure 6: The sample origin point of Dayr al-Barsha, Egypt, an ancient quarry and necropolis that was occupied since the Predynastic era.

(Esri, 2019a) Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

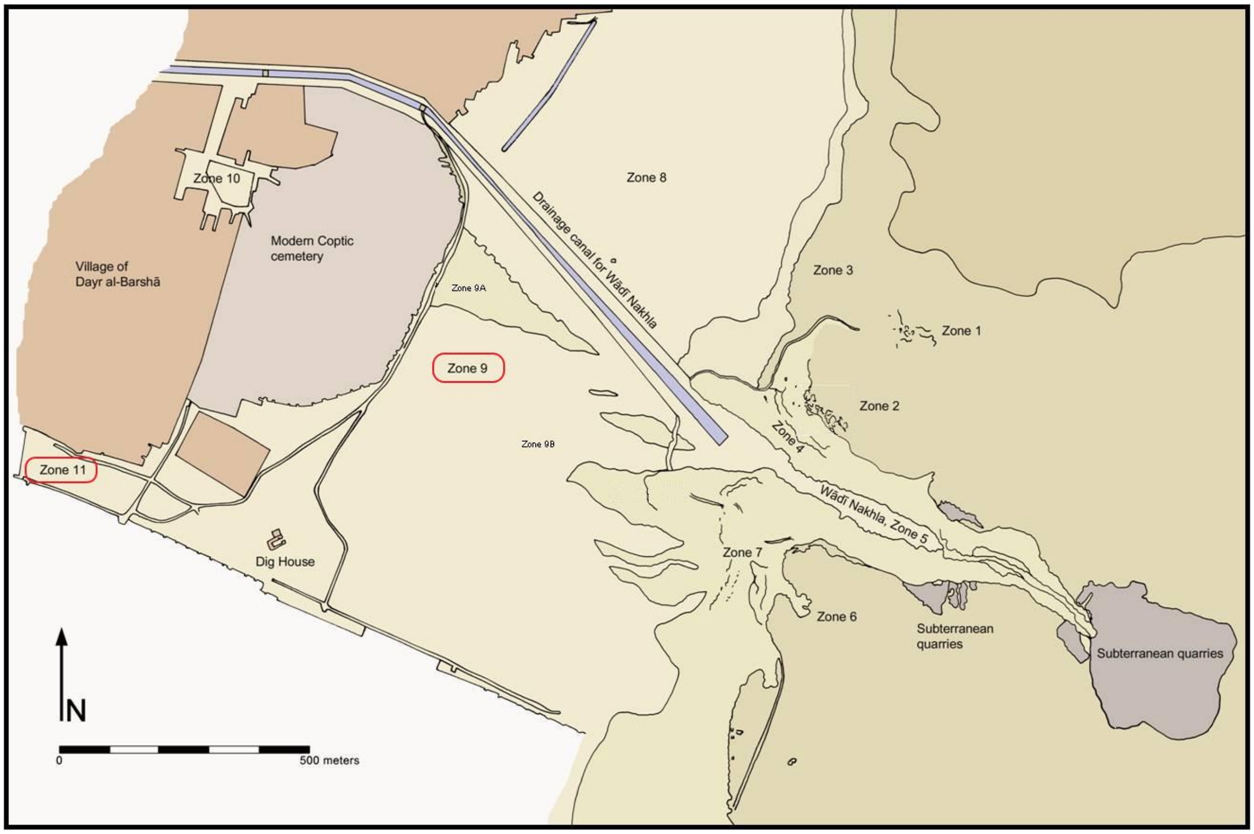


Figure 7: Site map of Dayr al-Barsha. The red circles indicate Zones 9 and 11 where the sample was excavated (De Meyer, Van Neer, Peeters, and Willems, 2005).

Twenty-five individuals were selected as they represented a random cross-section of the site’s population and had all the necessary skeletal elements (L. Williams, personal communication, August 12, 2019). These individuals originate from the Zone 9 excavation site which consists of shaft and shallow pit tombs which primarily date to the Middle Kingdom but were sporadically reused (Brovarski et al., 1992; De Meyer et al., 2005), and Zone 11, an area south and adjacent to the modern village of Dayr al-Barsha (Figure 7). Apart from one or two which still showed residual soft tissue or cartilage, the bones were completely desiccated and exhibited varying taphonomies ranging from a moth-eaten appearance, postmortem breaks, sand erosion, and bleaching. Provided that the articular surfaces were still intact, the bone shaft was not required to be present but had to be associated with an individual by provenience.

These 25 individuals did not leave Egypt, but they were photographed on location providing 1,510 pictures of all anatomical directions of the articular surfaces of the left and right glenoid, humerus, radius, and ulna. Upon initial inspection and siding, notes were taken considering two aspects. The first assessed the amount of the full articular surface in the frame of the photograph. The second was an initial assessment for OA characteristics such as porosity, lipping, and eburnation on the articular surface as OA characteristic are necessity for methodological testing. As a result of this vetting process, ten individuals were selected taking into consideration completeness, view of the articular surface, and OA involvement (Table 3).

Table 3: The 10 selected individuals of the 25 sampled from Dayr al-Barsha. Additional age and sex information provided by Willems (2006).

ZONE / SECTOR	FEATURE	SEX	AGE	NOTES
11/1 02J25/1/5	5540/13	-	-	Right distal ulna broken / missing.
11/1	5619/4A	Male	-	-
11/1	5717/1	-	-	-
11/1	5730/1	Male	-	-
11/1	5731/1	Male	-	-
09/10N55 1C	834/40	-	-	Individual was in the burial room.
09/47	630/15	-	-	-
09/53	764	Male	29	-
09/58	772/9	-	-	-
09/100	6014/14	-	-	-

Assessment Criteria

Once the initial assessment was complete, the criteria for evaluation had to be established. Buikstra and Ubelaker (1994) provides one of the widest criteria for OA evaluation where the observer is asked to determine the type and expression of the arthritic change and the extent of the joint surface or periphery involvement (p. 122). This was a logical starting point as it offered the most comprehensive data collection procedure that might elucidate the progression of OA - not just as an advanced pathology, but as a developing one. Also, because it was the most comprehensive, it also provided a baseline for data collection that needed to be met and exceeded if possible, with the new methodology.

Due to the preliminary assessment of the population, the limits of involvement were already known and not all categories were noticed, namely eburnation - but for the sake of completeness it has been included in the evaluation criteria (Table 4). It is interesting to note that the third category of protic involvement is a combination of the previous two, pinpoint and coalesced. This was not necessary as the two were able to overlap during the digitization process. The second part of the assessment where the extent of the periphery or joint surface is determined was not done at the time of assessment because the digitization process itself provided much more accurate quantitative data as will be discussed in the analysis. These assessment criteria were applied to any articular surface of the arm from the glenoid to the distal ends of the radius and ulna that was easily rendered in a single photograph; however, it was determined that conventional photography might limit the application of this and will be addressed in the best practices section.

Table 4: Criteria used for the assessment of OA changes in this research. Based on Buikstra and Ubelaker (1994).

Type	Degree of Expression	Characteristics	Location
Marginal Lipping	1	Bump or slight ridge – barely discernable	Extent of circumference affected by most severe expression in thirds
	2	Sharp ridge – peaks and spicules	
	3	Extensive spicule formation	
Porosity	1	Pinpoint	Extent of surface affected in thirds
	2	Coalesced	
Eburnation	1	Barely discernable	Extent of surface affected in thirds
	2	Polished surface	
	3	Polished surface with grooves	

Photographs

All 1,510 photographs of the articular surfaces were taken with a Nikon D7100 digital single lens reflex (DSLR) camera with focal length lens of 60 mm and a macro ring flash. The pictures produced were 6000 x 4000 pixels with a horizontal and vertical resolution of 300 dpi and were saved as .jpg extensions. This provided exceptional clarity of osteologically significant OA factors when zoomed in, but kept storage to a minimum. Each shot is between 6 and 8 MB in size with the entire collection approximately 10.5 GB stored entirely on one 2 TB portable hard drive for transport. Standard best practices for archaeological and forensic bone photography were observed with all elements photographed against a black felt background and photographic centimeter scale (Figure 8). This centimeter scale is important because it serves as a reference point when scaling the image into GIS later.

Figure 8: An example of the photograph composition and the detail provided featuring the left glenoid of the individual from Zone 9 630/15. The glenoid exhibits lipping and porosity (right) around greater than two-thirds of the margin.

With the exception of the scapula which had a singular lateral view of the glenoid, all other elements had multiple views of available anatomical directions and variations in between. For example, the proximal humerus was photographed anteriorly, posteriorly, superiorly, and an anterior-medial and posterior-medial angle in an attempt to render a complete surface of the humeral head and likewise this was done for the medial and lateral aspects of the radial head, the articular circumference of the ulna, and the distal end of the humerus. In the end, specific angles were selected that provided the largest aspect of the articular surface to be digitized (Table 5).

Table 5: Recommended photograph views for arm articulations.

Articulation	***Bone Area***	***View***
Glenoid	Scapula	Lateral
Humeral Head	Prox. Humerus	Recommend from medial side slightly posterior and superior
Distal Humerus	Dist. Humerus	Distal / Inferior
Radial Head	Prox. Radius	Proximal
Trochlear Notch	Prox. Ulna	Anterior
Proximal Radioulnar Joint	Prox. Radius	Medial
Proximal Radioulnar Joint	Prox. Ulna	Lateral
Distal Radioulnar Joint	Dist. Radius	Medial
Distal Radioulnar Joint	Dist. Ulna	Lateral
Radiocarpal	Dist. Radius	Distal / Inferior
Ulnocarpal	Dist. Ulna	Distal / Inferior

It was noted that there were some difficulties in rendering more three-dimensional joints in a two-dimensional space such as the humeral head and the distal humerus. Photographs of the humeral head that were obtained only showed about a third of the surface from any aspect. It was resolved that this could be mitigated in data collection by photographing the medial aspect of the proximal humerus from a slightly superior and posterior aspect where the center of the head is in line with the camera lens. Similarly, the PRUJ of the radius and DRUJ of the ulna exhibited the same issue with the entire articular surface occasionally unable to fit in a single frame. Gaps in the data will be noted on any diagrams and will be addressed in the discussion section.

Geographic Information Systems

Spatial information has been an important part of archaeology since the 1960s when the New Archaeology took interest in quantifiable space as a meaningful medium for human action (Wheatley and Gillings, 2002). As technology improved and became cost effective, the development of GIS as a powerful set of tools for rendering, storing, and manipulating data started to become widely used both in and out of archaeological contexts. The term GIS does not designate a specific set of software, yet rather it implies a computer database system that stores, analyzes, and visually represents spatial data and information (Bolstad, 2016). Because of this broad designation, there are many open-source and purchasable licensed products on the market that fall under this category with a variety of tools. While all of these could not be evaluated for use with this methodology, open-sourced QGIS was tested and was able to perform the digitization process; however, the analysis phase has not been explored. This methodology was created and tested using Esri ArcGIS Desktop Advanced version 10.6.1 specifically using the ArcMap application and associated Spatial Analyst and Geostatistical Analyst extensions.

Spatial data in GIS takes two forms, raster data and vector data but both can operate together or separately. Raster data falls into the category of organized cells with a value, while vector data takes the form of points, lines, and polygons used to represent underlying areas of a basemap or photograph (Bolstad, 2016). While GIS often focuses on maps, the underlying principal of the system is to utilize data and spatial relationships to render a model. A spatial data model is defined as a representation of elements in a spatial database and the relationship among them (Bolstad, 2016, p. 30). Not limited to landscapes, recent uses of GIS technology have revealed complex patterns in human behavior (Conolly and Lake, 2006), interpreted burn patterns in forensic contexts (Fojas et al., 2015), and analyzed bone microstructure (Rose, Agnew, Gocha, Stout, and Field, 2012).

GIS has had many useful forays into the analysis of the human body in both clinical, archaeological, and faunal contexts. The differential diagnosis of skeletal remains utilizes a spatial component in the distribution of lesions throughout the body (Ortner, 2011). This idea considers the body as a landscape through which a spatial pattern emerges and corresponds to a pathological condition. A similar concept has been utilized on the human body to enhance the outcomes of endoscopic microsurgery by employing GIS to provide detailed spatial analysis of colonic lesions (Imanieh, Goli, Imanieh, and Geramizadeh, 2015). Chapman and Stewart (2014) utilized raster overlays in GIS to compare the patterns of OA progression of the elbow (humerus and radius) and the knee (femur and tibia) in a population sample from the Erie County Poorhouse. Finally, in 2010, Orton devised a method using GIS to link data in to representations of faunal assemblages as a means to better facilitate the interpretation of data.

Considering the utility of GIS in data management and spatial analysis, it is in the interest of academic rigor and modernization of many interdisciplinary fields to develop a method of integrating the data collection and analysis of OA with GIS. GIS has been shown to illuminate patterns in space and by doing so the behaviors that led to them (Wheatley and Gillings, 2002). By recording exact positions of osteophytic development, porosity, and eburnation on the articular surface, data can be incorporated into a GIS database and provide a visually comprehensive pattern analysis of the, limb, individual, or population than would be offered through current aspatial means (Chapman and Stewart, 2014; Fojas et al., 2015). The resulting patterns of OA could offer new insights into patterns of motion, handedness, gendered differences of labor, and most importantly, the progression of the pathology (Jurmain, 1999). A GIS based method would not only provide improved visual spatial analysis, but also aid in the goals of standardization, comparison, digital collection, storage, replicability, and distribution of data which are embodied by the current standards (Bolstad, 2016; Lessa, 2013).

Considerations Before Input

After the sample has been obtained, photographed, and sorted, data entry can proceed but certain variables should be considered. Since GIS is a database system, the variables being entered and how they are being entered should focus on specific goals or research questions. Given the criteria defined by the OA data collection by Buikstra and Ubelaker (1994), there are quite a few questions that require answers.

Variables

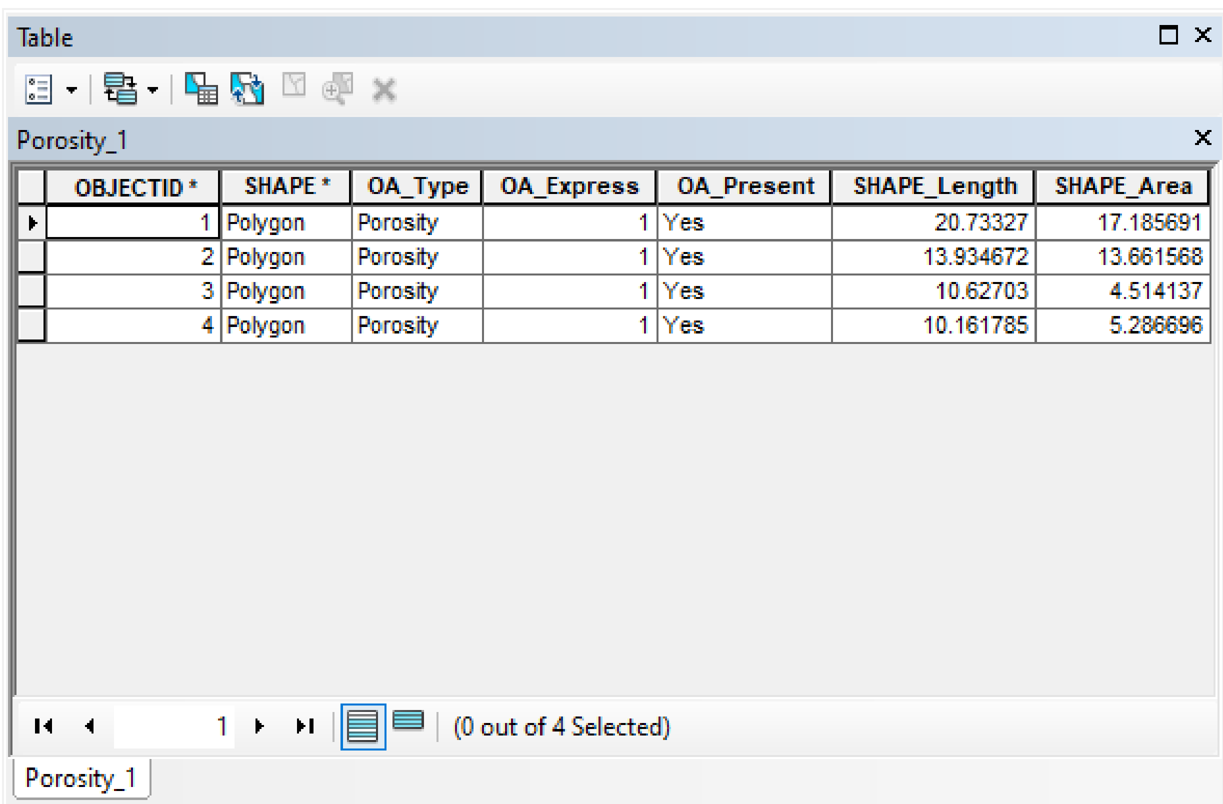
The first question requiring an answer is how much of the articular surface is involved with OA? This question can be broken down into numerous variables such as, total OA involvement, porotic involvement, lipping involvement, and, if present, eburnation. These variables can be broken down into further subsets i.e, the total amount of the surface that has porosity with expression of level one or level two. Secondly, the photographs of the skeletal elements being entered will read as raster data. This indicates that besides the RGB color data inherent in the .jpg file type, there is no other data assigned (OA or otherwise) within the photographs of the bones. The software cannot interpret bone from background. Therefore, the photographs will be read an entire 6000 x 4000 pixel image, not as an articular surface. This indicates that in order to accomplish the first goal of determining OA involvement on the articular surface and all other subsequent goals, the articular surface must first be delineated.

Shapefile Templates

The next point of consideration is, how might these goals be accomplished within GIS? Shapefiles are polygon shapes that can be constructed within GIS and are representative of the areas they overlay. They can be any size or shape and given any numerical or text attribute through the use of attribute tables. The process of digitization entails overlaying these polygons onto affected areas of the articular surface, therefore granting areas specified attributes while creating a digital map or representation of the surface. Since the assessment criteria defines these specific areas as the type and expression of OA characteristic on the articular surface, shapefile templates should be created for each of them and the attribute tables populated with fields for specific attributes that can be queried later if needed. This will not only serve to facilitate the process in a timely manner, but also provide consistency in variables and data entry.

The creation of shapefile templates can be accomplished through the 'Create Features' menu while in an editing session in ArcMap. Through here, variables can be named, data type defined, and default values entered. For example, for the OA features identified as porosity with a level one expression, a shapefile template for polygon features was created called Porosity_1.

Within the attribute table of Porosity_1, the following fields are created by default: OBJECTID which defines all objects created with a unique number and SHAPE which defines the geometry of the object created which is a polygon. Through the use of the ‘Add Field…’ menu within the attribute table, custom fields may be added to define the nature of shapefile Porosity_1. To define the type of OA manifestation, a field of OA_Type was added with a default text value of ‘Porosity’. Next, a field for expression of the OA type named OA_Express is added with a short integer data type default value of ‘1’. Finally, a slightly redundant third field was added to easily query for all OA occurrences on the bone surface if needed in the future. This field was defined as OA_Present with a default text value of ‘Yes’ (Figure 9).



Table

Porosity_1

OBJECTID *	SHAPE *	OA_Type	OA_Express	OA_Present	SHAPE_Length	SHAPE_Area
1	Polygon	Porosity	1	Yes	20.73327	17.185691
2	Polygon	Porosity	1	Yes	13.934672	13.661568
3	Polygon	Porosity	1	Yes	10.62703	4.514137
4	Polygon	Porosity	1	Yes	10.161785	5.286696

1 (0 out of 4 Selected)

Porosity_1

Figure 9: An example of a Porosity_1 attribute table with populated default values. SHAPE_length and SHAPE_Area will be populated after polygon construction within the database. Shown here are four polygons signifying Level 1 porosity on the radiocarpal surface of the left radius of individual from Zone 9/10N55 1C 834/40.

All subsequent attribute table templates can be constructed the same way for different OA expressions (e.g., Porosity_2, Lipping_1, Lipping_2 etc) (Table 6). While it is possible to integrate the OA manifestation types together and change the expression variable for polygons of different expression, this manner was chosen for its simplicity in color coding. The articular surface has its own polygon shapefile with the same custom fields. The field OA_Type is defined as ‘Articular Surface’. OA_Express is ‘0’, and OA_Present is ‘No’. The resulting shape area that will be created later will serve as the denominator for any computations on percent of coverage.

Table 6: A list of name and attribute table variables used to accommodate the OA assessment criteria defined in Buikstra and Ubelaker (1994). All fields were not represented in this population sample. SHAPE_Length and SHAPE_Area fields would be added by default.

SHAPEFILE	ATTRIBUTE TABLE FIELDS			
FILE NAME	**SHAPE**	**OA_TYPE**	**OA_EXPRESS**	**OA_PRESENT**
Porosity_1	Polygon	Porosity	1	Yes
Porosity_2	Polygon	Porosity	2	Yes
Lipping_1	Polygon	Lipping	1	Yes
Lipping_2	Polygon	Lipping	2	Yes
Lipping_3	Polygon	Lipping	3	Yes
Lipping_4	Polygon	Lipping	4	Yes
Eburnation_1	Polygon	Eburnation	1	Yes
Eburnation_2	Polygon	Eburnation	2	Yes
Eburnation_3	Polygon	Eburnation	3	Yes
Articular_Surface	Polygon	Articular Surface	0	No

The decision to place individual joints into file geodatabases stems from a focus on simplicity in the directory structure and the automated inclusion of the SHAPE_Length and SHAPE_Area fields within the attribute tables of all created polygons. These fields are imperative in determining how much of the articular surface is involved with the OA pathology. Not only this, but when assessing a combination of joints or total sample involvement larger conclusions can be made. These file databases are the recommended native data format for ArcGIS data with a maximum file size of 1 TB. It will work on all operating systems and handle large datasets for larger populations with photographs of greater resolution (Esri, 2019b).

The final concern before data input is color coding standards. As the output is rendered in a visual medium, it is recommended that a standardized system of colors be established lest arbitrary loaded colors lead to confusion when viewing the data. It was observed during the creation of this methodology that a custom style file could be created within the 'Symbol Selection' menu. If colors were named corresponding with the name of the shapefile they represented, then the color would be assigned automatically at the creation of the shapefile (Figure 10).

	R	G	B
Bone	244	237	229
Lipping_1	0	255	197
Lipping_2	0	197	255
Porosity_1	255	0	0
Porosity_2	255	0	197
Total_OA	115	0	76

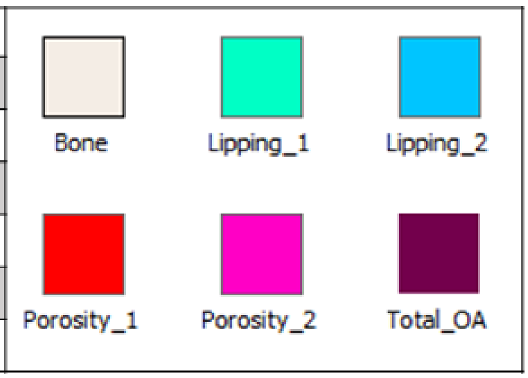


Figure 10: The color scheme and RGB data used for the OA shapefiles in Dayr al-Barsha sample. Construction of a premade style will ensure consistency in visual rendering. Bone was utilized for the Articular_Surface shapefile and Total_OA was constructed in the analysis phase.

IV: RESULTS

The variables mentioned in the previous chapter are not only important to expedite a comprehensive data entry process, but to also ensure relevant output for a variable or a combination of variables. Once these processes are completed, data entry can proceed which starts with the image input and scaling process, followed by final assessment and digitization When digitization is finalized this data can be analyzed in various visual and statistical manners including models and diagrams representing patterns within the joint, arm, or population (Figure 11). These topics will be addressed in procedural order with analysis consisting of examples of data presentation, visualization, and statistical analysis.

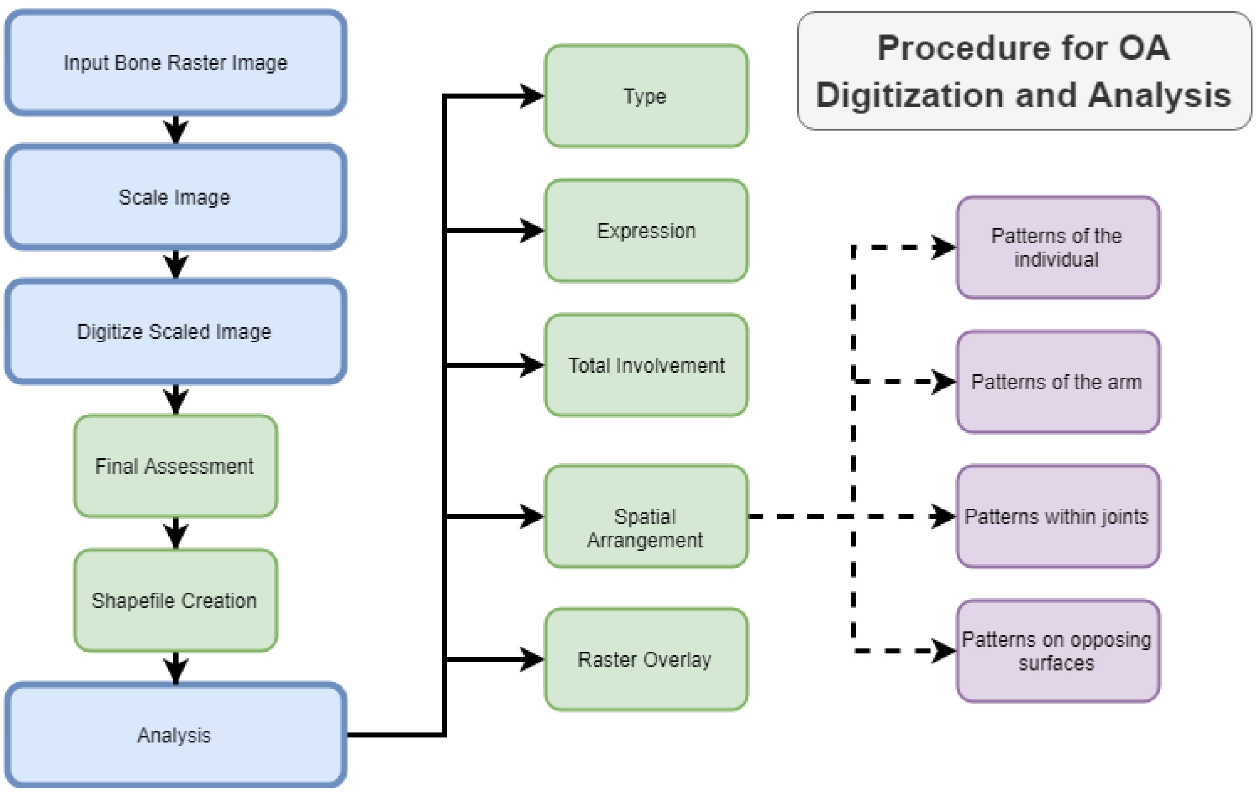


Figure 11: Initial image digitization and analysis process overview.

Image

Prior to importing the raster, the Data Frame Properties can be adjusted to be part of a cartesian coordinate system that utilizes meters. The use of a meter-based coordinate system will facilitate the measurement of objects within the GIS. The next step is to import the raster dataset into GIS. Adding a raster image to GIS is a simple procedure. By right-clicking on the file geodatabase that was created, an option to 'Import' then 'Raster Datasets' will emerge. Select the image of the articulation you wish to import. Once imported, the raster exhibits visual data in bands of red, green, and blue pixels. At this stage, the image can be adjusted, rotated, and gamma values changed to better highlight OA affected areas or adjusted for flash saturation of the image.

Scaling

Because one of the primary functions of GIS is the ability to show the spatial relationship between mapped areas, the ability to accurately quantify both the size of the areas and the distances between them is important. After the image import, the image exhibits dimensions that are excessive in comparison to the articular surface's true size. Therefore, in order to retrieve measurement data from the bones with relative accuracy, the image should be scaled back to original size. This can be accomplished using a combination of the 'Create Fishnet' tool, the centimeter scale in the photograph, and the 'Georeferencing' tool.

In order to scale the raster image, two grids need to be created; the reference grid and the picture grid. The picture grid is created based on a measurement obtained from the 'Measuring' tool of 1 cm on the centimeter scale in the picture which can be converted to millimeters. This grid will be limited to the extent of the picture. A second grid, or reference grid, will be constructed of the same unit dimensions of the picture grid,but with each unit equivalent to 1 unit within the coordinate plane. As a result, the scale for the articular surfaces is 1:1 GIS units to millimeters on the articular surface.

Having constructed the two identical but differently scaled grids, the two can then be georeferenced together. To accomplish this, four control points were positioned at the corners of the picture grid which were matched to their identical points on the reference grid. These control points will provide sufficient reference to perform a 1^{st} Order Polynomial transformation. Therefore, this transformation will shift, scale, and minimally rotate the raster image so that it fits within the boundaries of the four control points on the reference grid (Figure 12).

At this stage, the image is in proper scale defined by the centimeter scale in the photograph. This can be verified by using the 'Measure' tool to check the length of one of the blocks on the centimeter scale. If the scaling is correct, then the tool should read approximately 10 units. To retain these changes to the bone raster image, under the 'Georeferencing' menu choose 'Rectify'. Rectifying the image saves the changes as another file keeping the original intact. This completes the scaling process and all grids can be removed from the 'Table of Contents' leaving the scaled raster to be use as a basemap on which to overlay OA shapefiles.

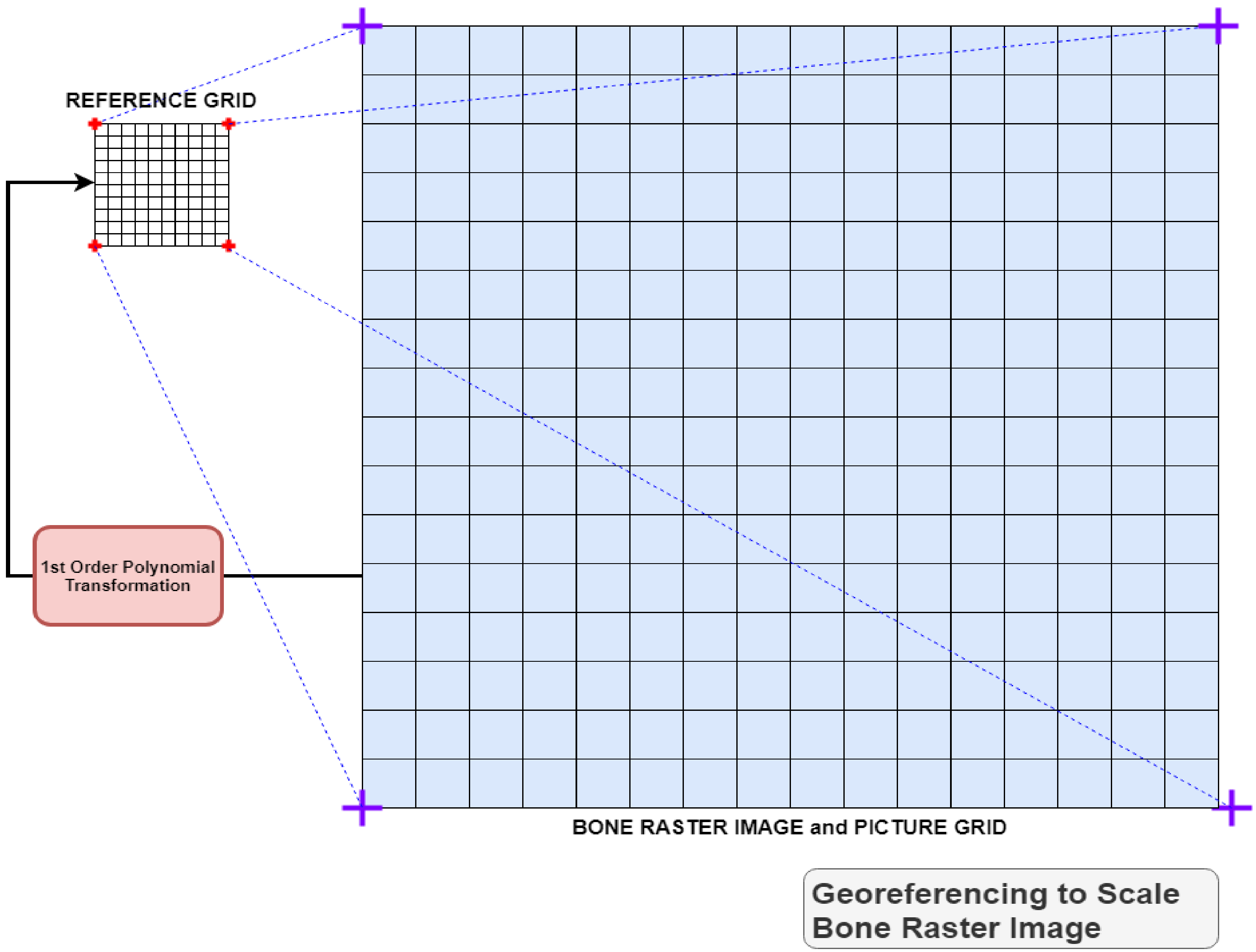


Figure 12: The process of georeferencing the underlying raster image to the reference grid using the 1st Order Polynomial transformation. This method uses four control points to shift the underlying raster image to the reference grid

Digitization

As one of the most common means to integrate data into the GIS, digitization is the process through which features are traced over a basemap and stored as layers within the system (Wheatley and Gillings, 2002). In the case of OA, these features are defined though the assessment criteria provided by Buikstra and Ubelaker (1994) which is reflected in the variables within the shapefile templates. Final assessment and shapefile creation ensure the input and future analysis of OA characteristics on the bone's surface.

Assessment

During the siding and sorting procedure there was an initial visual OA assessment that considered overall OA involvement on the bone. The second assessment is a much more detailed process and serves to accomplish three goals. The first is to delineate the extent of the articular surface. The second is to ascertain the types of OA exhibited on the bone in order to create the appropriate shapefiles. Finally, the third involves up-close scrutiny to determine where do these different types of OA manifest and the extent of this manifestation. Due to the improvements in digital imaging over the past decade, the imported and scaled bone raster images offer clarity at near microscopic ranges (Figure 8). Within the GIS the images can easily be zoomed and panned in order to determine not only the extent and type of OA, but to rule out residual sand, residue, and taphonomic features that might be interpreted as pathology.

For the method here, a group layer was constructed once this detailed assessment was completed. A group layer is not a shapefile in itself, but a collection of layers organized under a common subheading. This group layer was defined as 'Pathology' and within the options for this group, 'Transparency' was set to 60%. This will enable a level of transparency through all contained shapefiles where features of the bone surface are still discernable through the color coding (Figures 14, 15, and 16). The creation of the 'Pathology' group layer allows all layers within the group layer to be turned on or off as needed for a clearer view of the bone to compare the surface with the digitized polygons as well as providing a means to zoom to the 'Pathology' layer (Figure 13).

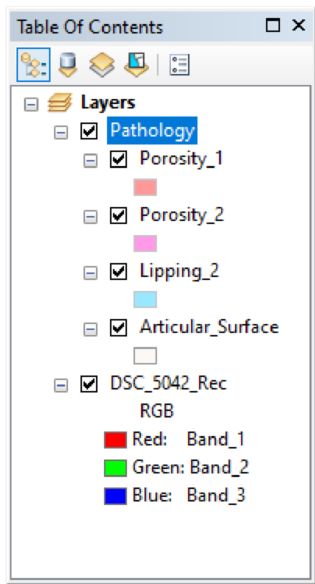


Figure 13: The Table of Contents structure for the group layer 'Pathology' for the right distal radius of individual from Zone 11/1 5731/1.

The first shapefile to be created should be for the articular surface as it sets the boundaries of the area being evaluated. This is created within the File Geodatabase for the articular surface by right-clicking the File Geodatabase and choosing 'Feature Class' under the 'New' menu. The files structure should remain 'Polygon Features' and match the coordinate system. When creating the shapefile, the default attributes for the 'Articular Surface' should be imported from the pre-configured template shapefile. Once this file is created, an editing session can be started where a polygon can be constructed through the use of the 'Construction Tools' under the ‘Create Features’ window. The process entails outlining the articular surface with a complete polygon (Figure 16). The polygons can be constructed using the mouse; however, digital tablets have been tested and have proven effective.

Subsequent shapefiles for porosity, lipping, and eburnation are created in the same manner. A single shapefile can have many independent polygons within the layer; therefore, it is not necessary to create a new shapefile for each instance of porosity at level 1 or lipping at level 2. Once completed, these shapefiles can be turned on or off independently or shown as multiple overlays within the confines of the articular surface layer (Figures 14, 15 and 16). It worth noting that as the polygons are created within the shapefiles in the file geodatabases, the SHAPE_Length and SHAPE_Area fields are created and populated with the measurements shown in the scale that was created during the scaling process. Selecting specific polygons within the attribute tables will highlight the corresponding polygon on the map allowing the researcher to identify specific polygons or run computations for complete OA coverage. For the right radiocarpal articulation of individual 11/1 5731/1, the polygon area for OBJECTID = 1 is equal to approximately 19.8 mm^2 (Figure 16).

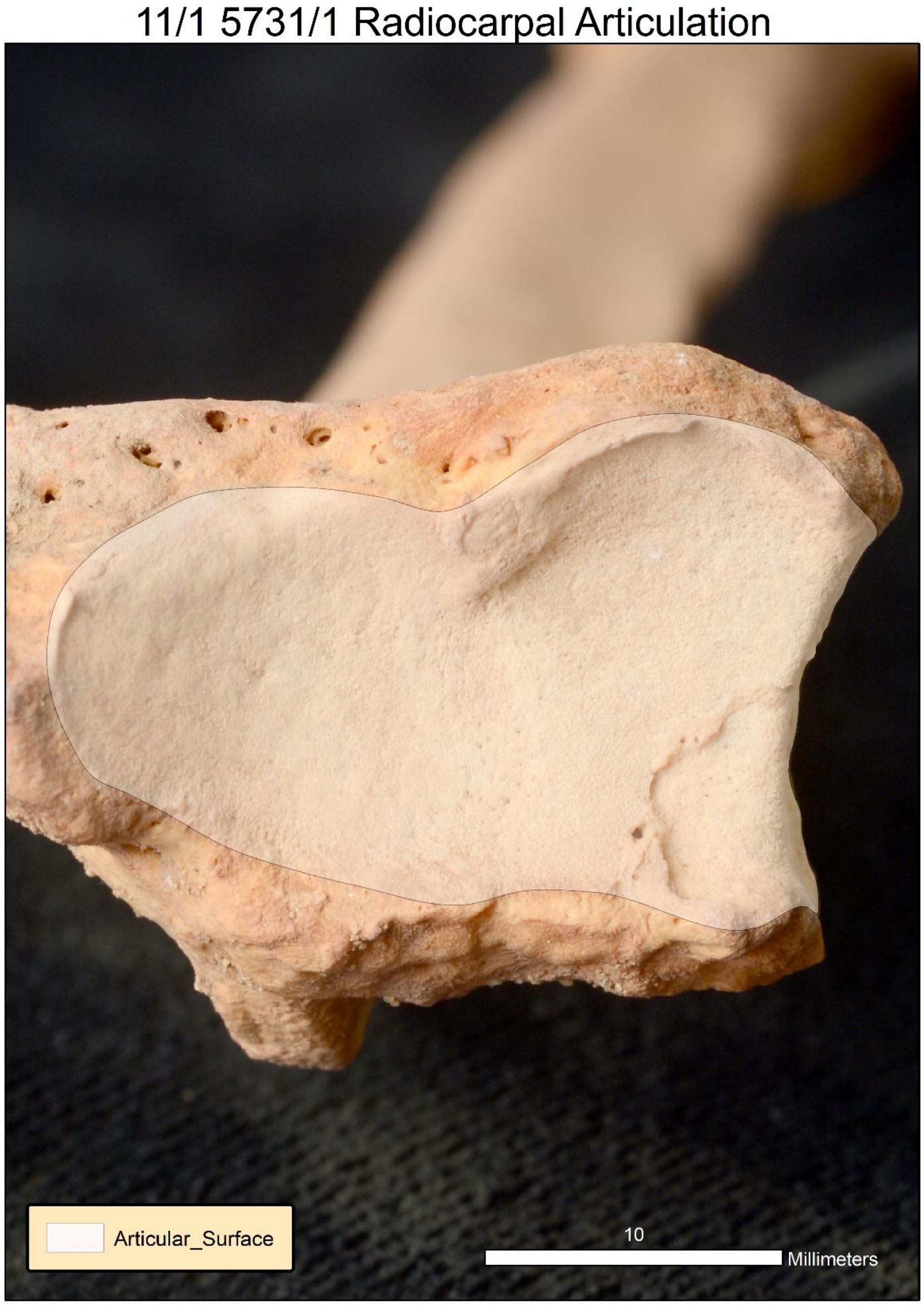


Figure 14: Right radius radiocarpal articulation of 11/1 5731/1delineated by the Articular_Surface shapefile with 60% transparency. Anterior is top. Medial is right.

Figure 15: Right radius radiocarpal articulation of 11/1 5731/1 with additional shapefiles overlays for OA types. Anterior is top. Medial is right.

OBJECTID *	SHAPE *	OA_Type	OA_Express	OA_Present	SHAPE_Length	SHAPE_Area
1	Polygon	Porosity	1	Yes	25.410238	19.793997
2	Polygon	Porosity	1	Yes	15.711932	6.608921
4	Polygon	Porosity	1	Yes	8.846573	4.578319
5	Polygon	Porosity	1	Yes	10.948725	6.55278
6	Polygon	Porosity	1	Yes	10.25777	6.930343
7	Polygon	Porosity	1	Yes	15.347854	10.186453

Figure 16: Porosity_1 layer and attribute table for right radius radiocarpal articulation of 11/1 5731/1 showing selection of OBJECTID = 1(blue outline) and corresponding highlighted polygon. Note SHAPE_Length and SHAPE_Area have been tabulated automatically

This procedure is consistent for any articular surface that can be rendered within a single frame. Some articular surfaces will not show any OA but for the sake of inclusion of the entire limb, it is recommended that the images be scaled and the articular surfaces defined. This will aid in defining the full percentage of a limb or joint complex. Examples of these analyses will be explored in the next section.

Analysis

With the bone photographs at scaled sizes, the resulting spatial and quantitative data can be analyzed to better understand not only the biomechanical implications involved with OA, but the possible development of OA within the skeleton including stages and hotspots. This analysis will be broken down into sections exploring the possibilities that exist as a result of OA data collection within GIS. These will include examples of quantitative assessment of specific types of OA manifestations, assessment of the degrees of expression, and total involvement. Subsequently, this quantitative data can be paired with both digitized and modeled representations of the articular surfaces where patterns within the individual, within joint complexes, and within the arm can be compared and visualized.

Assessment of Type

Because the variables are isolated in the attribute tables, it is possible to determine the extent of each individual manifestation of porosity, lipping, and eburnation within the sample - either individually or as a whole. While lipping and osteophyte formation at the margin of the joint surface is a marker of OA, eburnation has often been denoted as more important trait as it is proof of the loss of articular cartilage (Waldron, 2012). However, while it is a definitive OA trait, the presence of eburnation serves as an indication as to the severity and may only exist in extreme cases (Altman et al., 1986; Rothschild, 1997). Rothschild et al. (1997) brings porosity into this debate as well, citing no definitive correlations between OA and porosity of the bone surface in his study of the knee. With all of these traits being highly debatable, it is logical that their presence or lack thereof would be of interest in future studies of the pathology progression and therefore worthy of documentation and analysis.

With the ability to query the OA shapefiles for both SHAPE_Area and OA_Type, accurate measurements can be obtained for specific OA characteristics within a joint or in a larger group. Within individual articular surfaces, simple computations for total OA involvement based on type can be accomplished numerous ways. For example, if we pose the question: what percentage of the left glenoid surface of 09/100 6014/14 exhibits porosity in any form? This can be answered quite a few ways. The simplest is to shut off all active layers except for Porosity_1 and Porosity_2 and then by using the ‘Select Features’ menu choosing ‘Select by Rectangle’ and drawing a rectangle around all remaining OA polygons. Once highlighted, utilizing the ‘Selection’ menu, select ‘Statistics’. The result will be a statistical analysis of the selected polygons separated by layer (Figure 17). These summary tables can be used to construct percentages, either manually or programmed to be computed by the GIS system, to determine the area affected. The computation for the percent of porosity affected area would consist of the following:

$$\frac{\text{SUM of Porosity\_1 SHAPE\_Area} + \text{SUM Porosity\_2 SHAPE\_Area}}{\text{Articular\_Surface SHAPE\_Area}} \times 100$$

The final outcome of this equation is about 13.82% of the surface is involved with porosity or, to be more detailed, 119.04 mm^2 of porosity affecting an available 861.38 mm^2 of the articular surface. Pairing this information with the digitized image or even a generalized modeled image creates a map that not only allows the researcher to interpret the spatial patterns and coverage with greater accuracy, but also allows the reader insight into how the researcher interpreted the OA on the surface (Figures 18 and 19).

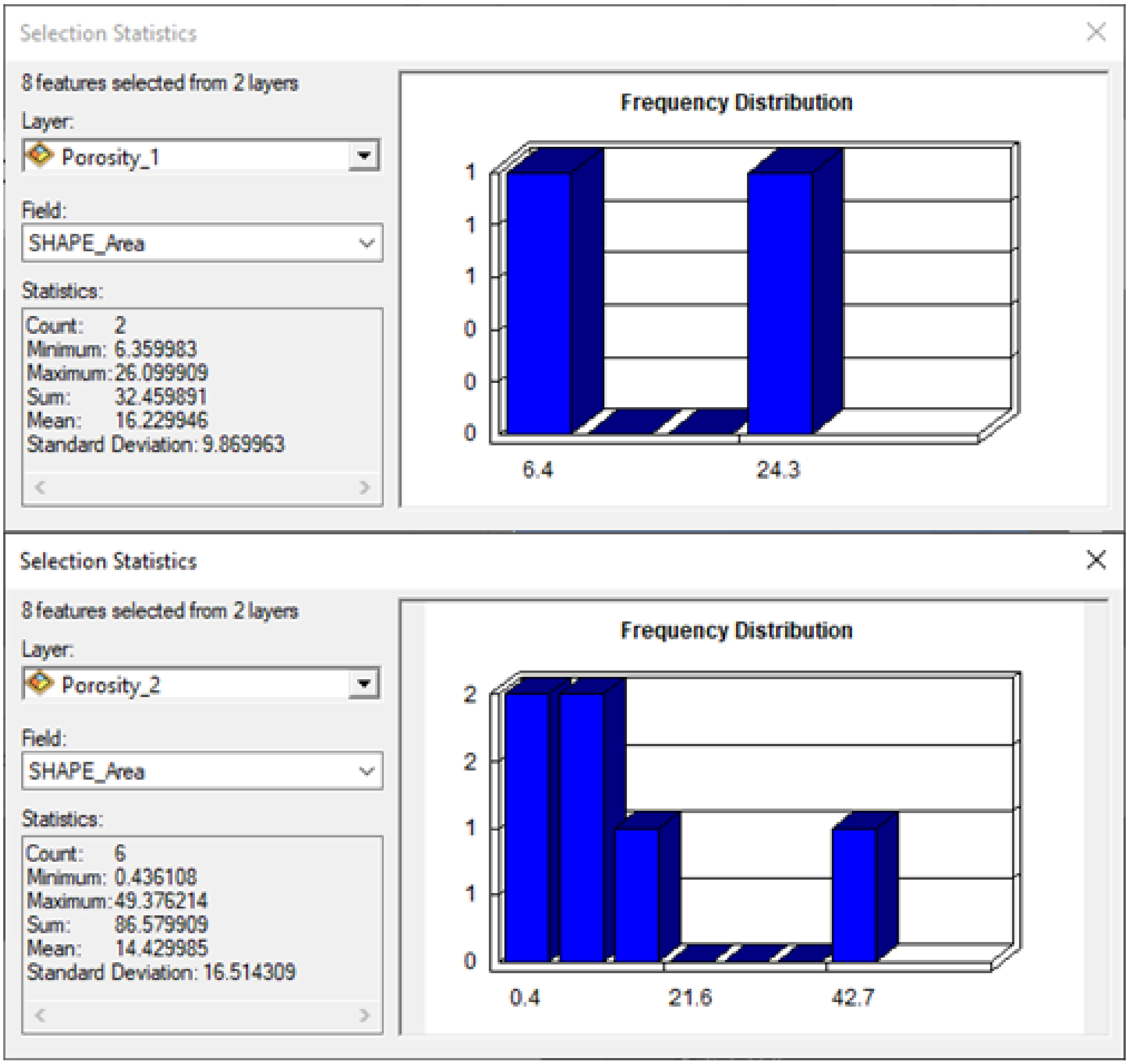


Figure 17: Statistical results from the porosity layers of 09/100 6014/14's left glenoid. Summations of the SHAPE_Area can be used to show the full involvement of porosity or porosity at a specific level of expression.

Figure 18: Example of digitized porotic OA characteristics on the left glenoid of 9/100 6014/14.The digitized overlay allows for reinterpretation and isolation of selected variables with spatial data. All measurements in mm^2. Superior top, anterior left.

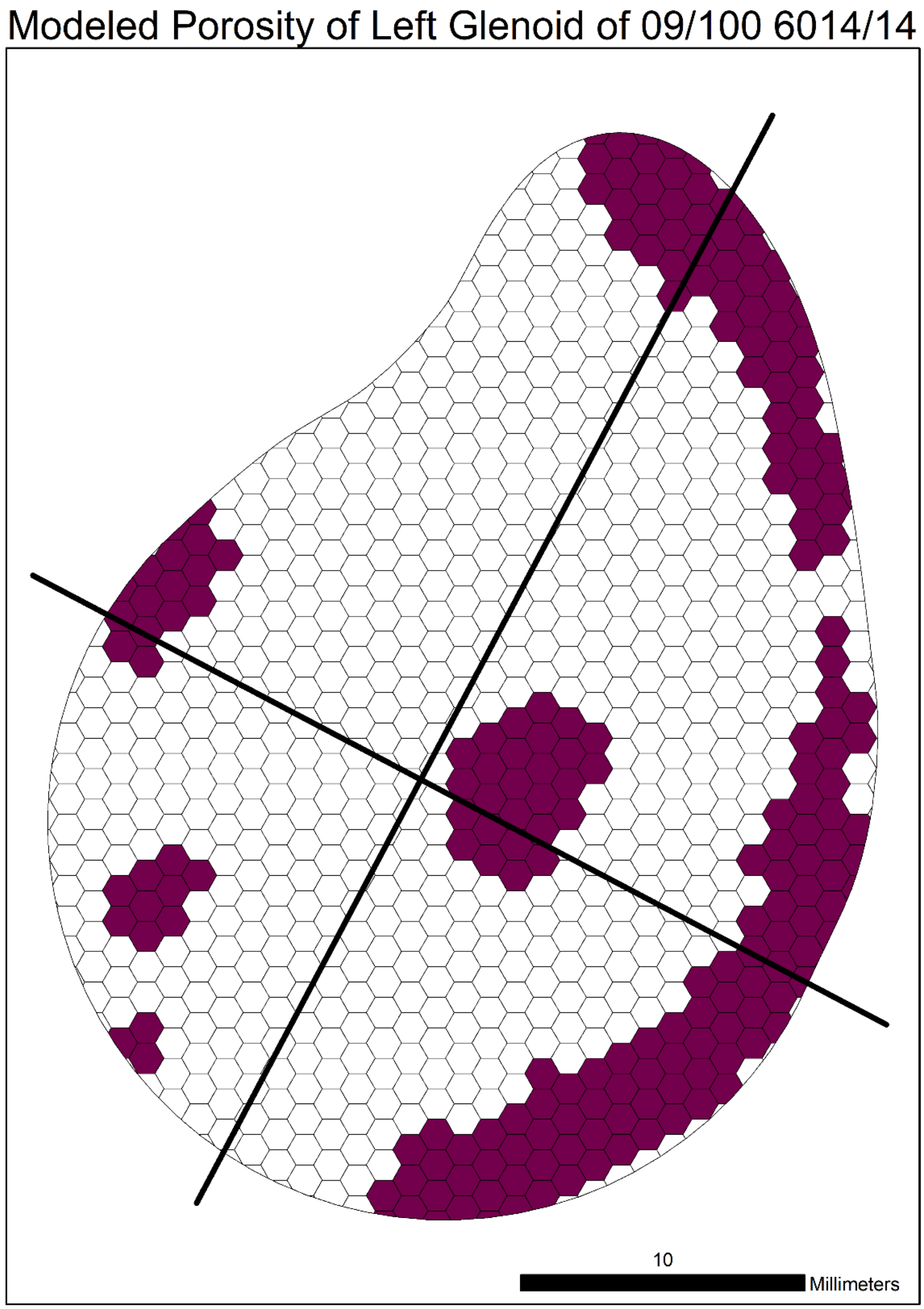


Figure 19: Modeled porosity of the left glenoid of 09/100 6014/14. Modelling exhibits a representation of the actual surface and offers clarity of spatial areas affected by OA manifestations. Hexagons shown in 1 mm^2. Superior top, anterior left.

The ways by which data is represented here is by no means the singular way that GIS can be configured to represent it. Labels, equations, and even joined tables can be configured to determine statistical analysis and report within map outputs. It is highly recommended that if analysis proceed outside the articular feature into larger contexts (e.g., the joint or the arm) that the individual shapefiles from the individual articular surfaces be merged into larger groups in order to better facilitate the querying of data between joints, limbs, and the population sample. For quantitative questions relating to, how much of a specific OA characteristic is on the joint surface within the entire population or to compare between individuals or even burial areas, it is best to utilize the 'Merge' geoprocessing tool to integrate all OA and articular surface shapefiles into a singular shapefile for the articular surface in question (Figure 20).

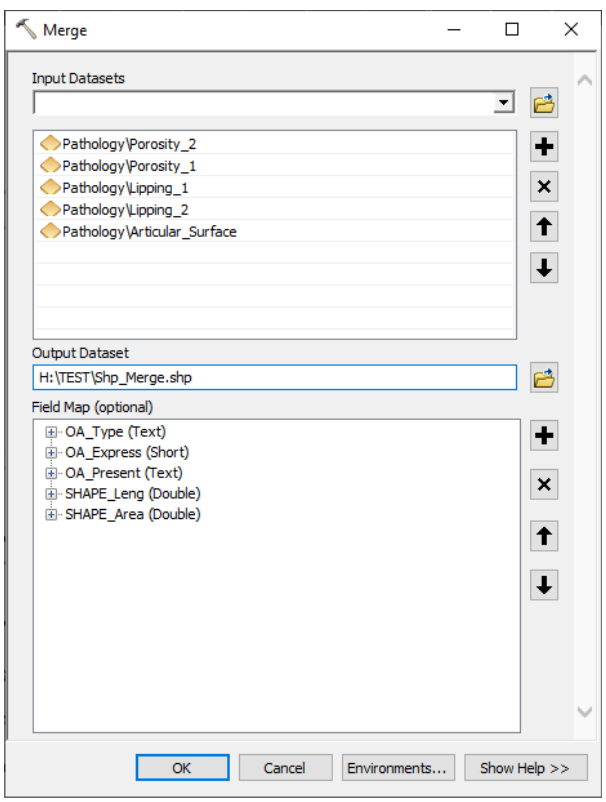


Figure 20: The 'Merge' geoprocessing tool which enables the combination of multiple shapefiles and their attributes into a singular shapefile. This can be done with individual surfaces, joints, arms, or sample populations.

Once these files are merged into a larger table for the articular surface, it is recommended that additional attribute fields be assigned within the merged shapefile so that queries can be made that can focus on the individual and the joints within a larger context. These attributes are the side, the individual designation of the individual, the articular surface or element in question, and the joint complex (Figure 21). Subsequent combinations of merged shapefiles will result in a shapefile for the entire population. This attribute table can be exported and imported into various other software applications for further manipulation.

All layers for the Dayr al Barsha sample were merged into a singular database that included the additional attributes (Figure 21). Once completed, larger questions about the involvement of specific OA manifestations can be answered. The merged shapefile can now be queried by using the 'Select by Attribute' sub-menu under the 'Selection' menu. From here, custom queries built from Structured Query Language (SQL) expressions can be created to select data fitting specific questions (Figure 22). For example: how much total lipping involvement is on the left glenoid of 09/100 6014/14? The resulting expression to query this information is: *"OA_Type" = 'Lipping' AND "Element" = 'Glenoid' AND "Name" = '09 6014/14' AND "Side" = 'Left'* where the database will search the attribute table selecting only those that match. The attribute table should highlight those entries fitting this query and once selected, running 'Statistics' will result in a statistical analysis including the summation of all OA involved on the articular surface. The resulting computation finds that out of the 861.36 mm^2 of the articular surface, approximately 166 mm^2 is affected by lipping in any form – or approximately 19.27%. These queries can be used on any aspect of the attribute table including OA_Express and OA_Present or any combination of attributes including limiting to areas above or below a specific size.

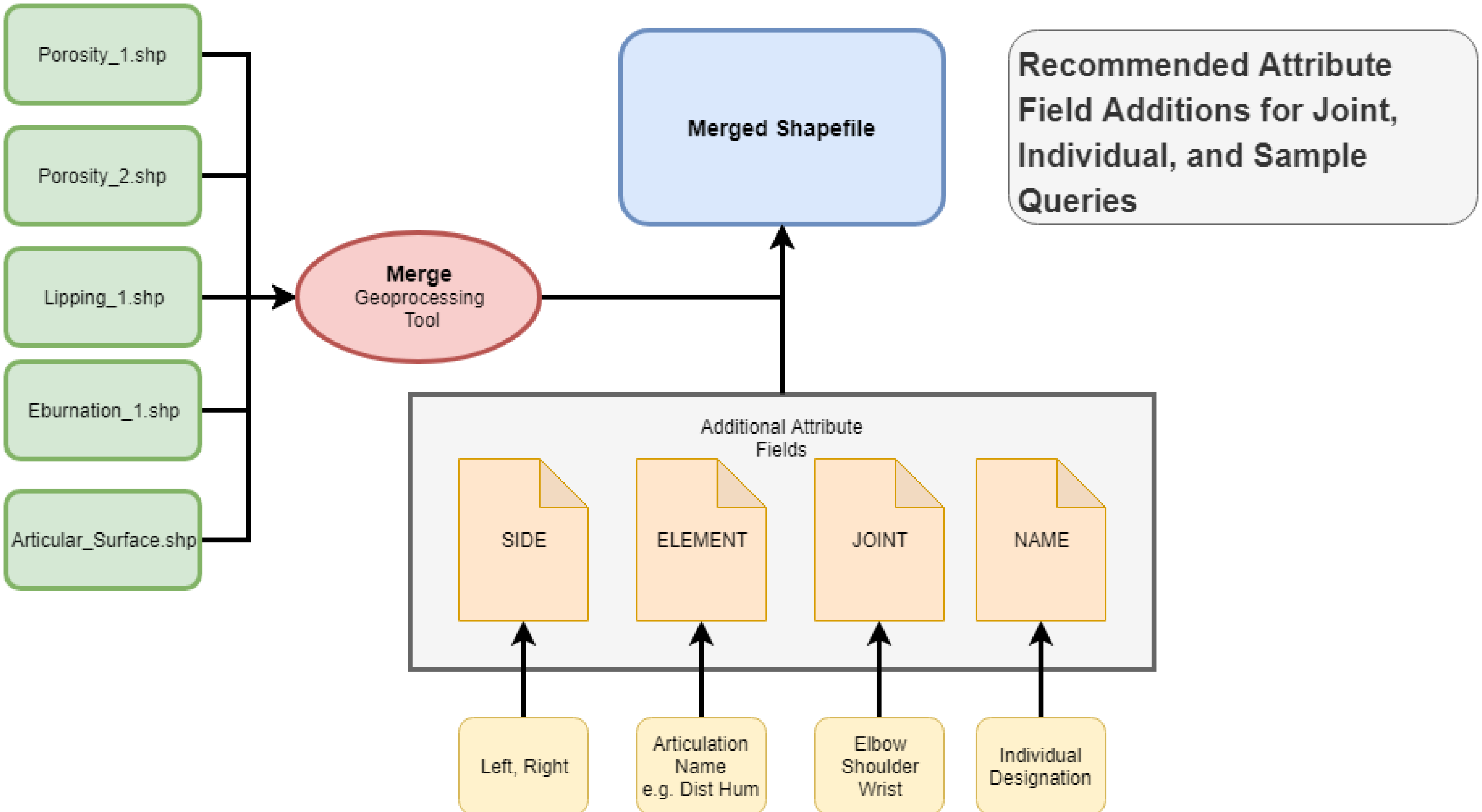


Figure 21: Additional file attributes recommended to facilitate queries into a wider context including comparisons between joints, limbs, or individuals.

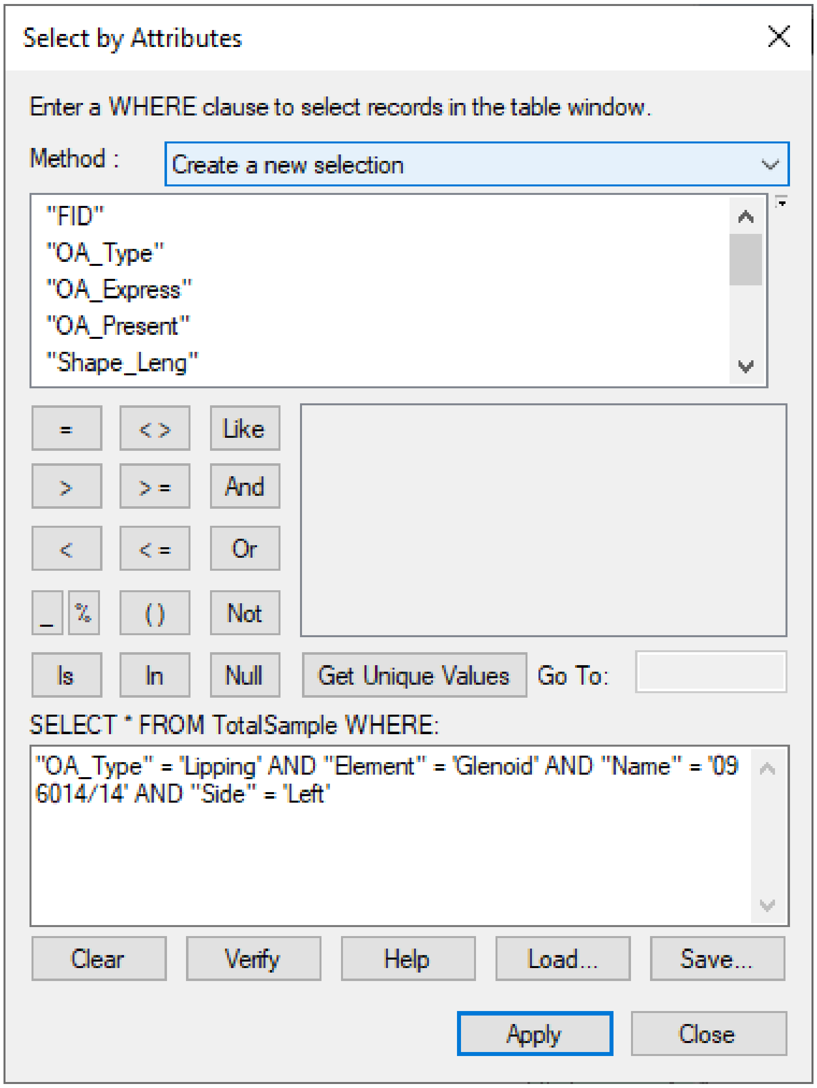


Figure 22: Select by Attributes screen where custom SQL commands can be used select and limit data dependent on the research question. The query selects data values for lipping on the left glenoid of 09/100 6014/14.

Similarly, using the same database this approach can be used on joint complexes to answer the question: what is the percentage of lipping within the left elbow of 11/1 5731/1? When queried and summarized for articular surface area, the total articular surface within the elbow is found to be 2128.77 mm^2 and the query for lipping finds 158.7 mm^2 involvement and a total lipping within the elbow joint to be approximately 7.5%. With the additional attributes, analysis of an entire arm and larger scaled analysis can take place. Not only can these new variables isolate specific individuals within the sample, but can also isolate joints and individual articular surfaces in larger contexts. Consider the question: do specific manifestations of porosity occur evenly within the arm? Dependent on the number of skeletal elements available, this data is easily obtained and digitized rasters or models can be presented within the GIS or exported for configuration in different forms. (Figure 23 and 24).

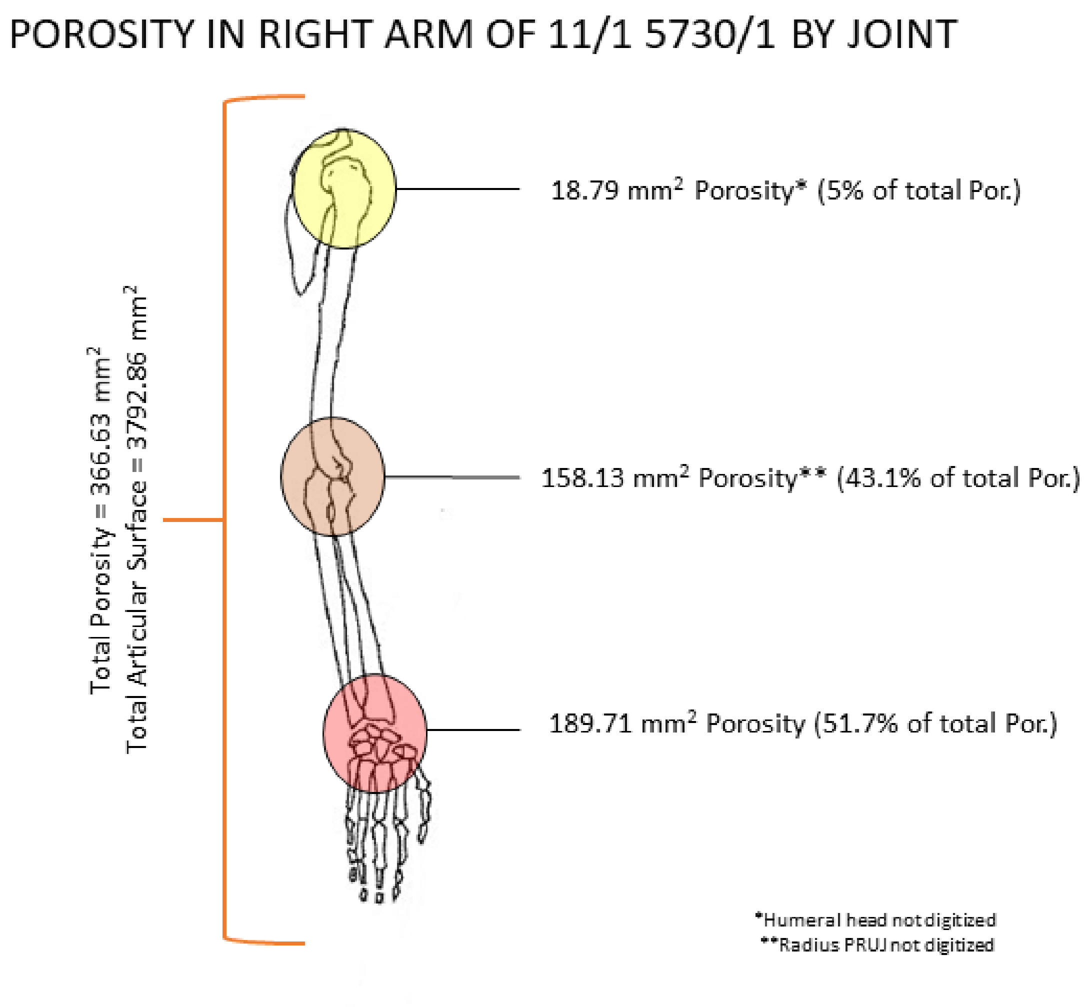


Figure 23: Example of quantitative data use after database extraction. Even without spatial data, the precise quantitative data and simple extraction could be used to reveal patterns of OA progression.

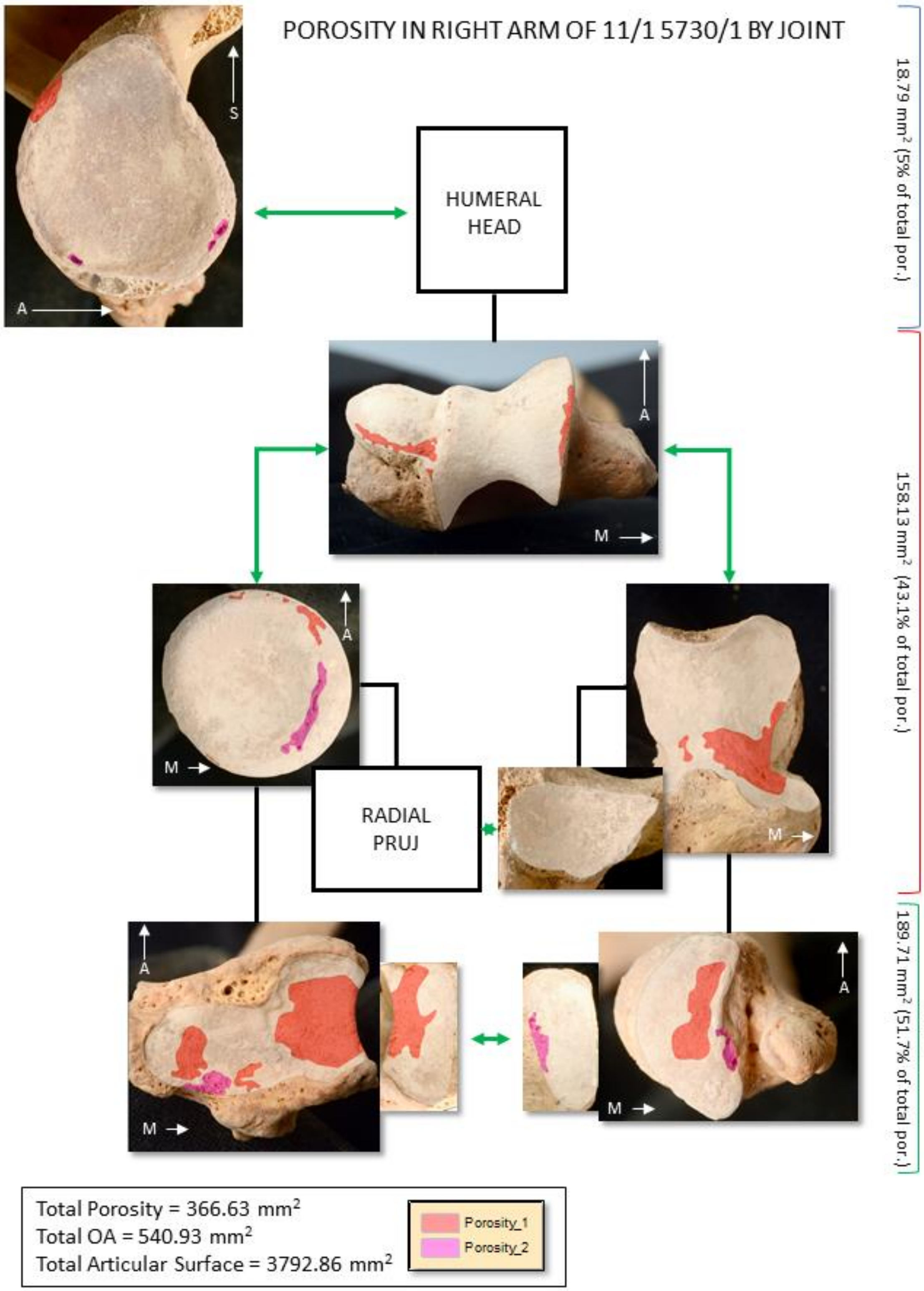


Figure 24: Example of using the digitized bone rasters as a means for providing spatial data within porosity manifestations within the right arm of 11/1 5730/1.

Assessment of Expression

Figure 25: Level 2 expressions of OA on the right distal humerus of 09 834/40. Level 1 layers were disabled allowing a view of more extreme OA expression in the humero-radial articulation.

Because of the attribute OA_Express within the sample database, it is possible to change the direction of research questions and ask which areas express a more severe manifestation of OA than others. Much like sorting from type, expression can be queried through the use of SQL commands in the ‘Query By Attributes’ menu selecting for the OA_Express attribute for comparisons of which articular surface or joint complexes have the more extreme OA expression or largest area of OA expression in a singular area or in total. Additionally, by disabling the appropriate layers, specific locations of OA expression can be isolated on the articular surface for comparison (Figure 25). Through the same means that OA_Type was assessed, the extraction of data from the database can provide nearly limitless interpretations to be paired with visual representations of data from the individual to the sample.

In the assessment of OA expression, the interpretation of hotspots, or areas with more extreme OA expression within a population or individual, could indicate areas of the joint under extreme stress or possibly the progression of the pathology. The raster manipulation tools within GIS are uniquely suited to create raster overlays in an attempt to spot these areas of significance. Based on Chapman and Stewart (2014), this procedure entails migrating the OA_Express values out of the OA and articular surface attribute tables into raster datasets. This is accomplished using the ‘Polygon to Raster’ tool. These raster datasets are then georeferenced to a model outline using known markers on the bones surface such as the extent of the maximum width, height, or most anterior point. Once this is completed, the use of the sum function within the ‘Cell Statistics’ tool provides a new raster where the cell values indicate the sum of overlapping OA_Express values in the raster cells. A higher number indicates persistent occurrences of OA severity in specific areas (Figures 26 and 27). Subsequent population sample overlays for individual articular surfaces can be either compared or interpreted through a quadrant structure coinciding with anatomical positions to better describe and place OA occurrences in lieu of having a defined coordinate structure or diagramed as full limbs (Figures 27 and 28).

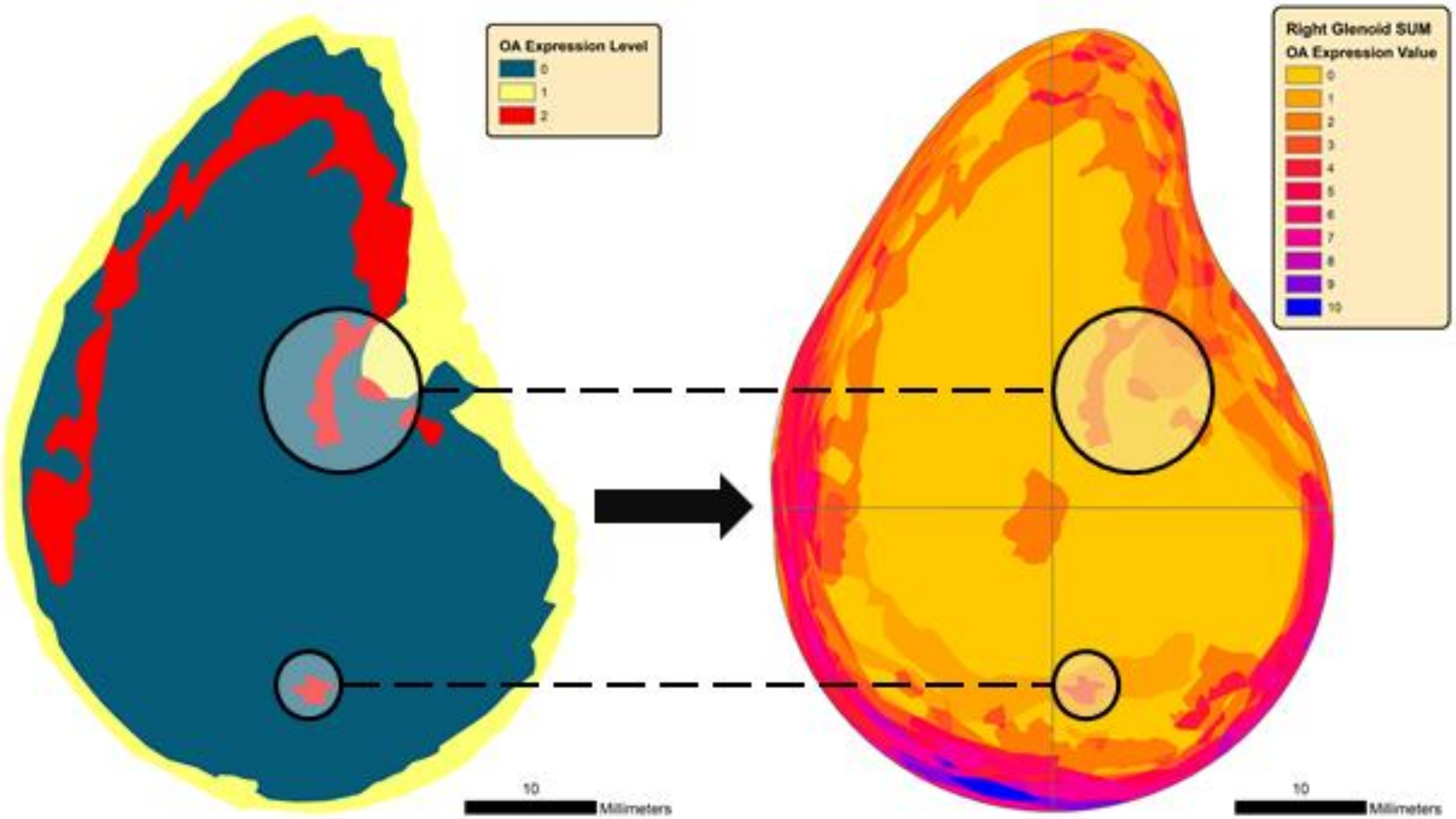


Figure 26: Expression raster of the right glenoid of 09/47 630/15 (left) and overlay of right glenoid (n=7) from population sample (right) selecting for manifestation of higher OA expression through summation of overlays. Population overlay (right) indicates higher OA expression in the posterior-inferior aspect of the glenoid. Black circles illuminate individual (left) OA aspects within the population overlay.

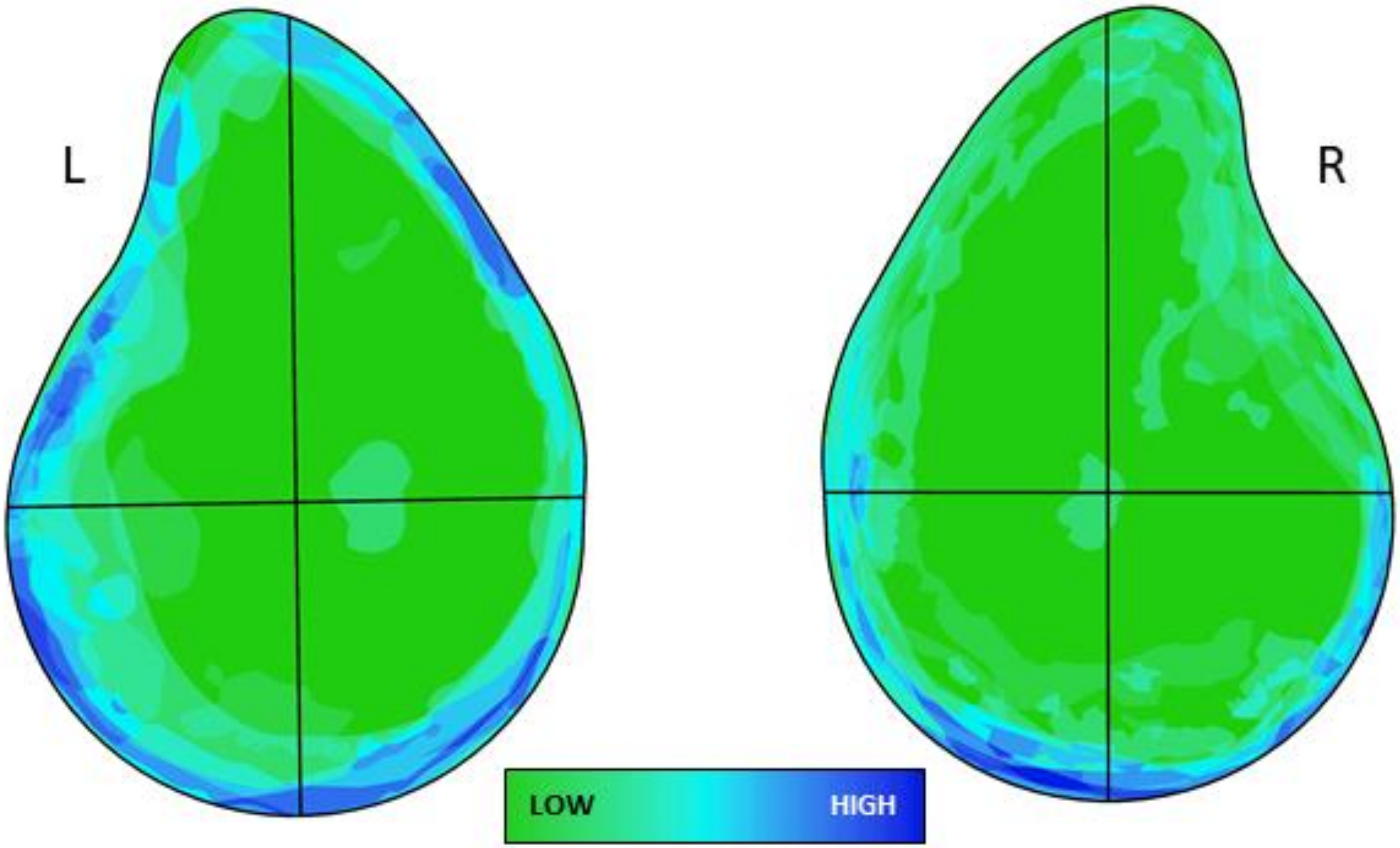


Figure 27: Comparison of the population sample's glenoids by a summation of spatially overlapping OA_Express variables. The left glenoid (n=7) exhibits increased OA expression on the overall margin while the right (n=7) is isolated to the posterior-inferior margins.

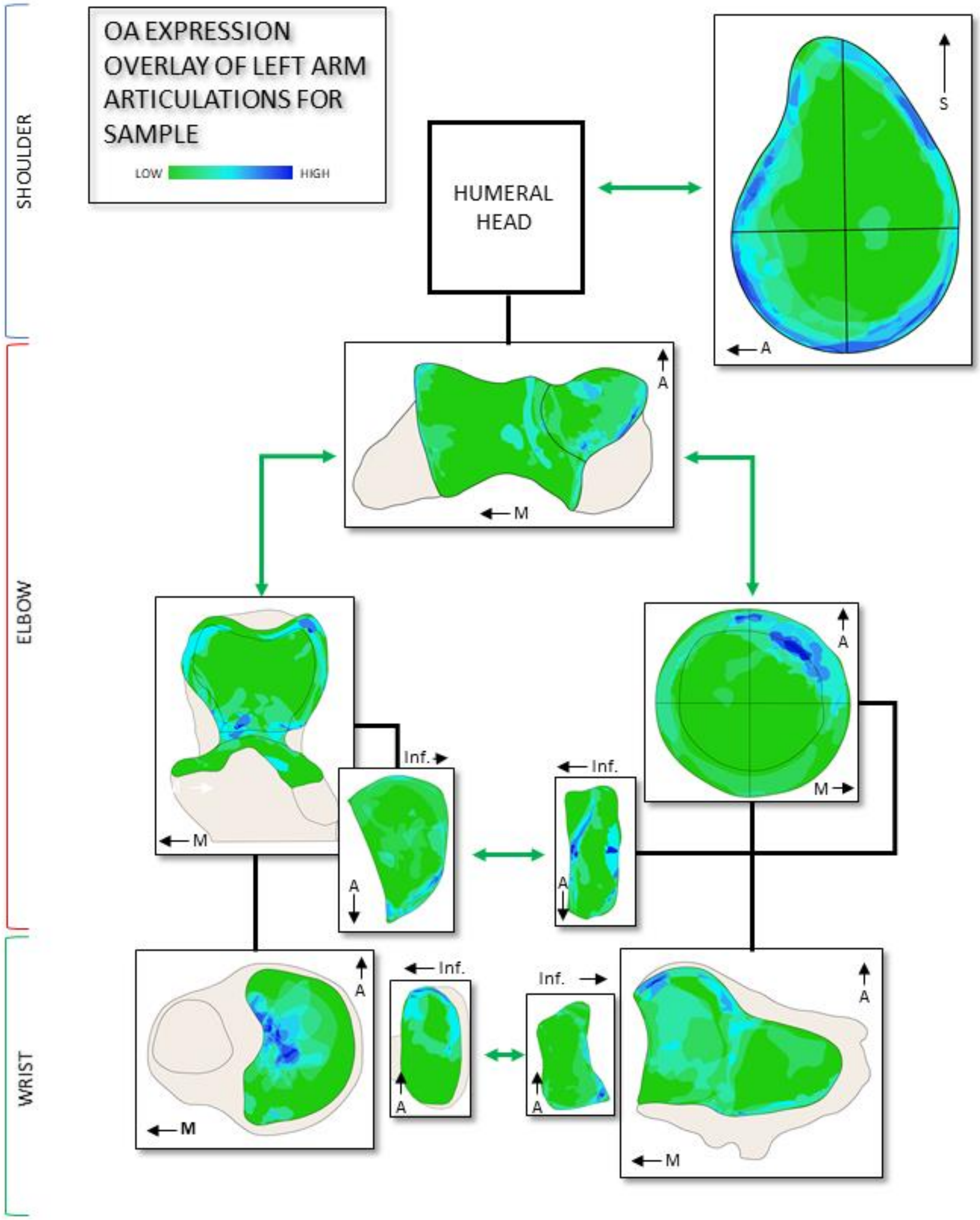


Figure 28: OA hotspots of the articular surfaces of the left arm in the population sample.

Assessment of Total Involvement

Considering the number of variables within the population database, it is not difficult to query for the full extent of OA involvement on the articular surfaces of the arm. As a statistical value that is wider in scope than the OA type or OA expression, a simple query of *"OA_Present" = 'Yes'* will return all available OA database entries regardless of type or expression. For the sample this number is approximately 7077.03 mm^2 of OA affected area out of 66120.27 mm^2 of available articular surface. This indicates that approximately 10.7% of the surface is affected by characteristics of OA in this sample. However, when considering the total OA values, overlap must be taken into account of which this section will focus on

When two separate polygons overlap, the area computations are perceived as two individual values. Therefore, the GIS will calculate the overlapping area twice when considering total OA numbers. This was not widely perceived within the sample, but more so between different OA types than analogous ones (Figure 29). For this reason, 'Total_OA' shapefiles were created during digitization using the 'Union' command (Figure 30). This command may also be used when large aspects of OA on the surface are shown to overlap for a more accurate area measurement. Because of this omission in the overlap, 'Total_OA' shapefiles using the 'Union' command should show less than or equal to the merged non-union OA shapefiles. This effect is minimal with a less than 1% difference in this sample, yet further development for this issue will be considered in the future to improve accuracy.

Much like the shapefiles for the OA involvement and the articular surfaces, the Total_OA shapefiles can be merged into larger files to interpret total OA development within the arm, individual, and sample; however, much more must be taken into consideration when interpreting these results. Results of comparisons between total OA involvement between right and left arms should consist of an equal number and type of left and right elements. For example, of the 9 left and 9 right articular surfaces available of individual 11/1 5730/1 the left side shows 744.78 mm^2 OA involvement of a possible 3945 mm^2 of articular surface – or approximately 18.8%. In contrast to this, the right exhibits 528.15 mm^2 OA involvement of a possible 3792 mm^2 of articular surface or 13.9%. While this data can further isolate to the area of the arm having the most involvement, this data could be used to test research questions focusing on patterns of bilateral asymmetry within a population.

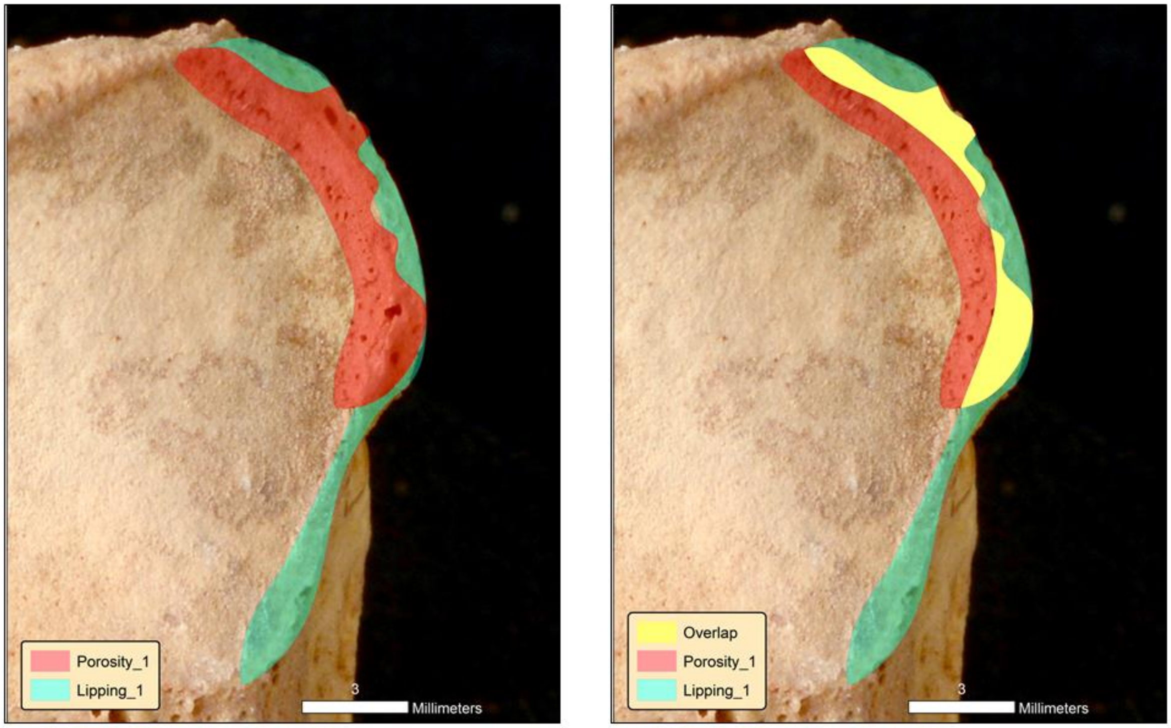


Figure 29: Overlapping OA manifestations on the right proximal ulna of individual 11/1 5730/1 (left). The yellow area (right) indicates areas of overlap that can often be counted twice in total OA affected area totals. Proximal is up, lateral is right.

Figure 30: Total_OA shapefile for left proximal ulna of individual 11/1 5730/1. Total_OA shapefile is constructed using the 'Union' option eliminating the double counting *of the overlapping areas. Total_OA area is 33.27 mm*^{2}*. Proximal is up, lateral is right.*

Assessment of Spatial Arrangement

In using GIS, not only can the quantitative data be improved in the areas affected by OA manifestations, but the resolution of this information can be improved by the inclusion of spatial data. It has already been illustrated how the digitization of the articular surfaces has been shown to retain the spatial placement of OA lipping and porosity (Figures 15, 18, 24 and 25); however, modeling this placement in various resolutions might elucidate generalized patterns occurring on the articular surfaces (Figure 19). By creating a grid structure within a stylized model of the bone shape, assessment between individualized areas can be made and generalized forms can be compared. This can include patterns within similar articular surfaces, patterns within the arm, and patterns within the joint. Each will be briefly addressed in the following section.

Utilizing the same bone model outlines used to constrain the data within the OA hotspot assessment, square grids were created within the boundaries of these forms at 20 mm^2 for larger surfaces (Figure 31), and 10 mm^2 for the smaller joint surfaces such as the PRUJ and DRUJ. These sizes were selected to accommodate the variations in bone structure but not to generalize the patterning excessively where a single porotic area would imply development within an entire quadrant of the surface. Squares were utilized within the tessellations rather than hexagons or triangles because the arrangement of the gridding structure allowed for a better labeling and comparison. It is noted that hexagonal tessellations may be utilized as well because of their rounded structure conforms to the curvature of the surfaces as shown in Figure 21 in 1 mm^2 form. For more rounded structures such as the glenoid and the radial head, the grids are aligned to bisect the surface into four quadrants to better facilitate comparisons and possible relationships to biomechanics. Other structures prone to more complex variations in structure such as the distal humerus were more difficult to create this alignment and as a result these grids are not aligned to anatomical positions, yet can still be ascertained and compared. Grid labeling is an arbitrary procedure but should be uniform throughout articular surfaces as it will serve as the basis of comparison. For the purposes of this methodology, the left sided elements' anterior sides begin with the letter 'A' with the rows alphabetically advancing posteriorly down the cells. The columns advance numerically from the medial to the lateral position. This will be mirrored on the right side for easier comparison between sides with the right sided elements' anterior sides also beginning with the letter 'A' with the numerical advancement of columns also from the medial to the lateral side (Figure 31).

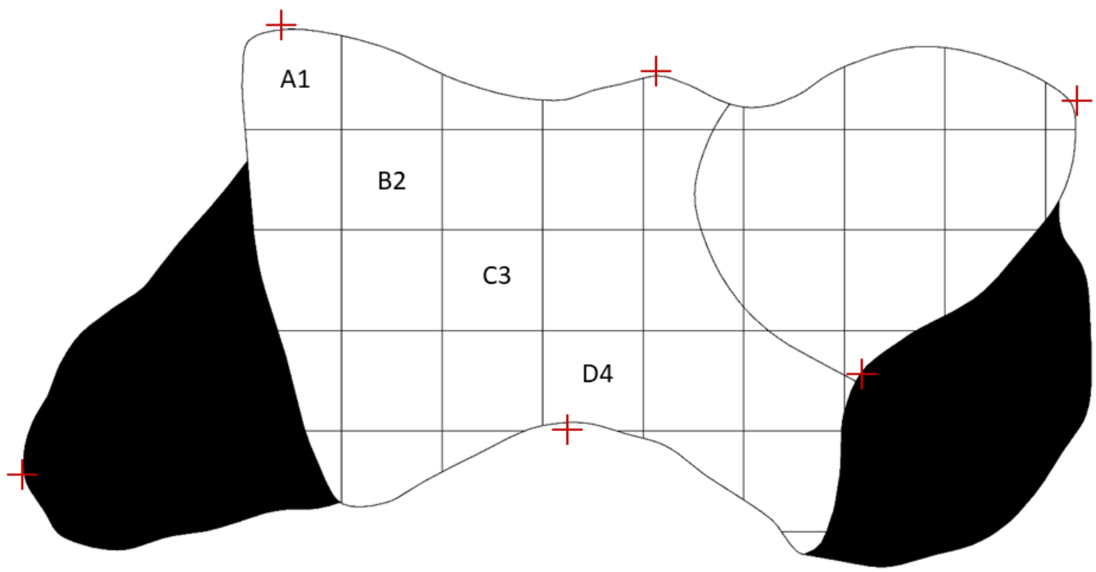


Figure 31: Stylized model of the left distal humerus with grid overlay. Examples of the number system where the anterior to posterior rows advance alphabetically and numerically medially to laterally. Right sided elements will mirror this overlay so that like affected areas can be easily compared. Red crosses indicate alignment points.

The models can be placed over the existing digitized bones using known landmarks to best align the models. For example, the distal humerus used the most lateral and inferior point of the capitulum, the most medial part of the medial epicondyle, and the most anterior and points of the anterior and posterior trochlea (Figure 31). Each element should follow a set alignment configuration to ensure consistency within the evaluation. Once the element is aligned, the 'Select By Location' tool under the 'Selection' menu can be used to highlight the cells intersecting with the digitized OA characteristics, providing a generalized pattern of OA development within the model overlay. This pattern can then be compared between similar articular surfaces, within the joints, within the arm, or even show patterns between opposing articular surfaces.

Similar articular surfaces can include like sided or opposing sides of a singular articular surface. The left and right distal humeri of 11/1 5540/13 were modeled and showed drastically different patterns of development from each other with the left exhibiting a more developed pattern from the A1 to C1 regions with development in the lateral most point of the capitulum in the A8 to A9 region. In contrast to this the right distal humerus exhibits no development in these regions but exhibits development in the D6 through F6 region without showing on the capitulum surface (Figure 32). Through the overlays, research questions focusing on the development, progression, or comparison between populations can be facilitated in a generalized manner and at a resolution of the researchers choosing.

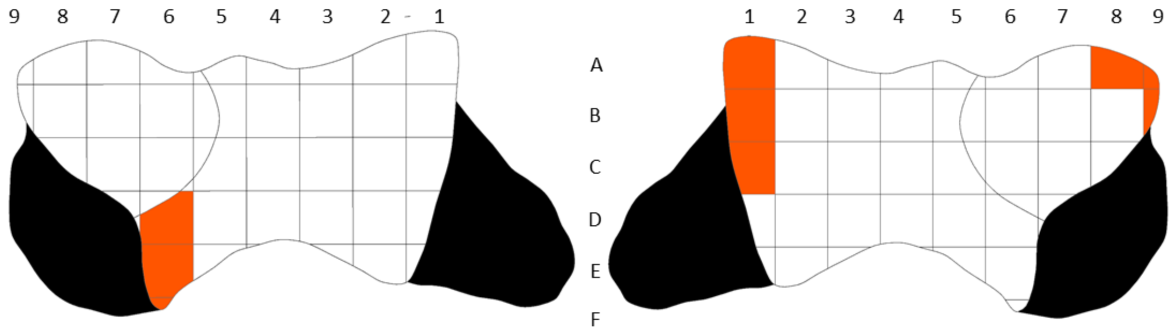


Figure 32: OA manifestations of the right and left distal humeri of 11/1 5540/13 modeled for comparison. Each orange square represents OA manifestations occurring within 20 mm² square of surface area.

With the generalized models of OA development, areas corresponding to anatomical positions and areas corresponding to contact during movement may become more apparent. When viewed as an entire limb, these generalize patterns within the articular surface can be combined for a larger assessment into the development of OA within the arm and the mechanical factors that may cause them. Assessment of the joint in its entirety can also be used to elucidate patterns in OA development or corresponding repetitive motions that are reflected in patterns corresponding to biomechanical factors (Angel, 1966; Merbs, 1983). These can also be used to compare similar joints within affected individuals.

Figures 35 and 36 illustrate the technique of this joint comparison within individual 11/1 5540/13. The tessellations were selected to include any point of OA manifestation intersecting the square tessellations. The results are two drastically different patterns between the left and right elbows for individual 11/1 5540/13. The left elbow shows significantly more development in the radial head, proximal ulnar, and PRUJ areas than the right. More detailed observations between similar structures can be initiated using a grid labeling structure (refer to Figure 34) but for the purpose of evaluating the elbow joint in its entirety, the general segmentation and specific articular surfaces suffice for a sub-unit of assessment. Contrasting development in the proximal radius between the elbows is readily apparent as is a different pattern within the proximal ulna with the left exhibiting more overall development within the trochlear notch along the medial edge than the right (Figures 33 and 34).

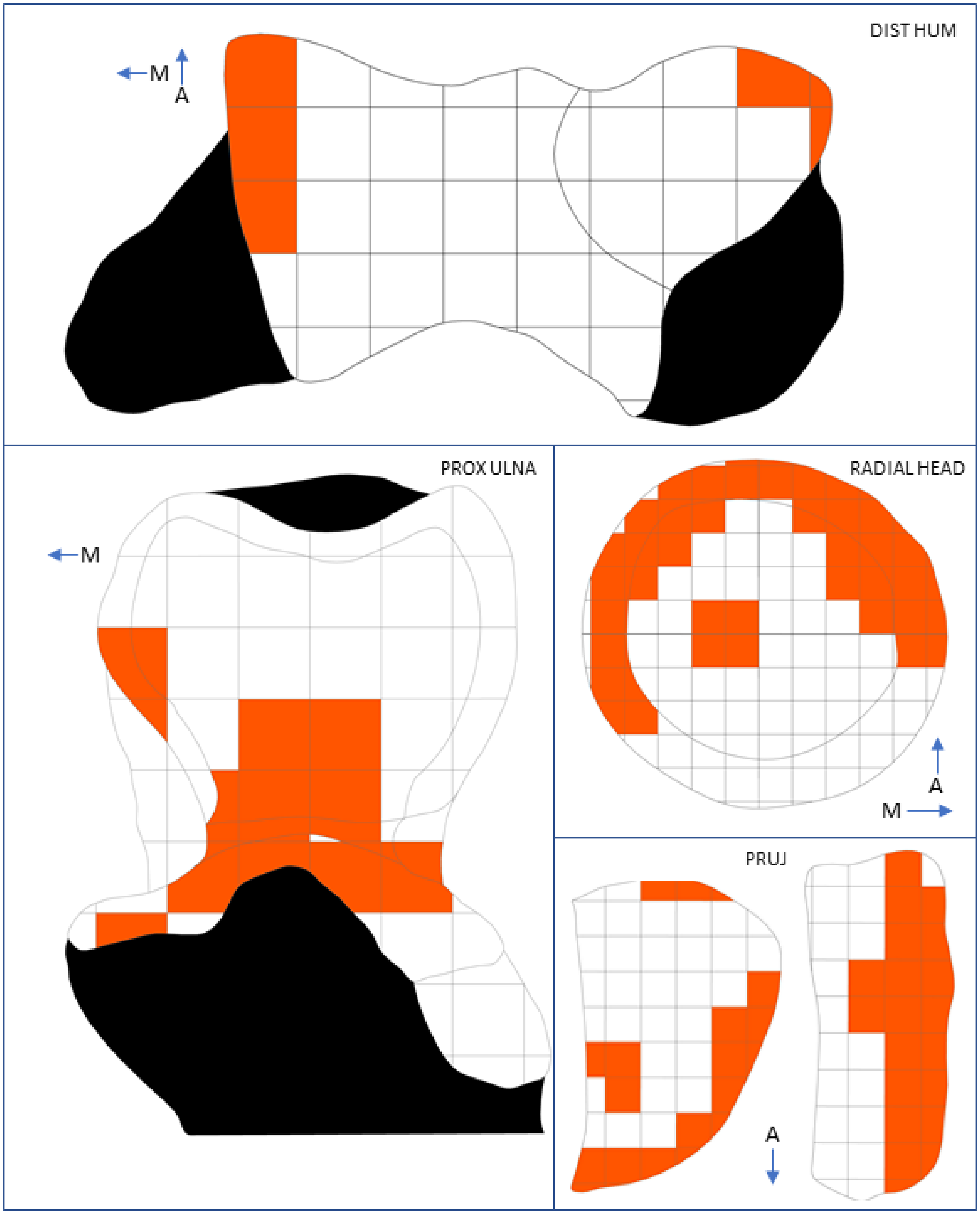


Figure 33: Generalized OA development within the left elbow joint of 11/1 5540/13. Orange shading indicates OA manifestations occurring within the proximity of the square tessellation (20 mm² for distal humerus and proximal ulna, 10 mm² for radial head and PRUJ).

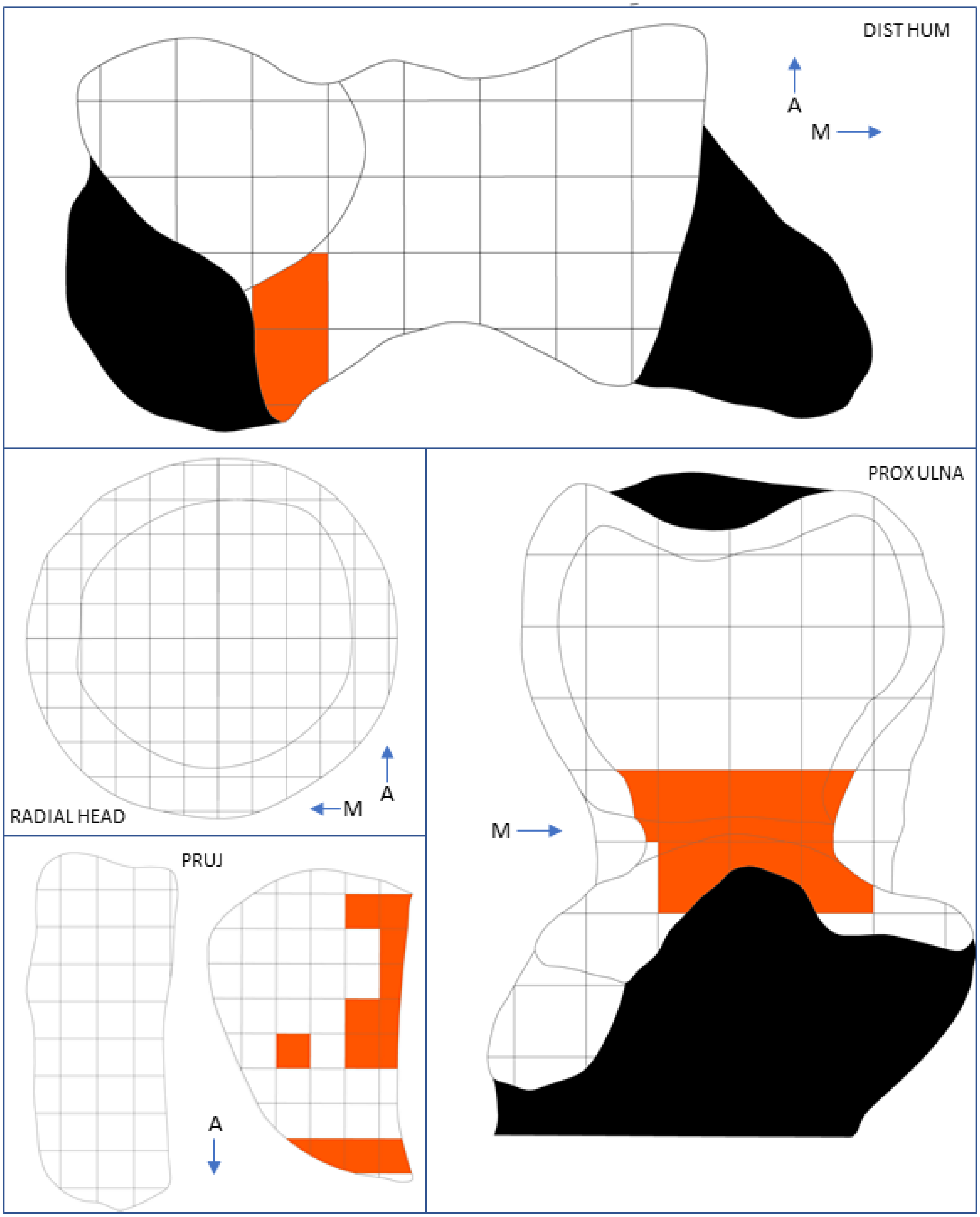


Figure 34: Generalized OA development within the right elbow joint of 11/1 5540/13. Orange shading indicates OA manifestations occurring within the proximity of the square tessellation (20 mm^2 for distal humerus and proximal ulna, 10 mm^2 for radial head and PRUJ).

The left arm of individual 09/100 6014/14 is the optimal limb to illustrate pattern analysis capability within an entire limb because the proximal humerus was photographed in a position where the articular surface could be assessed and digitized. While this offers a complete limb, it also provides data that could be used to evaluate questions that might be answered within a larger population sample. Both the posterior glenoid and humeral head show similar pattering in areas that, in a resting position, see considerable contact. However, this is not the case within the contact points on the distal humerus. The radial head and proximal ulna show no OA development while the distal humerus does. The PRUJ both show development in areas of contact, yet while the distal ulna shows considerable manifestations this is not shown equally in its radial counterpart (Figure 35).

While this information may seem initially confusing for those anticipating seeking a linear development of the pathology, it is worth to note that the OA development modeled here is based off the Total_OA and that limiting the OA characteristics to porosity or lipping may exhibit different patterns. For example, even though the distal left humerus of 09/100 6014/14 displayed only a level 1 expression of porosity this could indicate only an initial development of the pathology which would may not be sufficient to initiate a response from the opposing surface. These changes are also noted in the 09/100 6014/14 glenoid and humeral head articulation which exhibit level two expressions and affect opposing articular surface areas. Given the data within the GIS database, these questions can be addressed in significant detail through modeling both expression, type of OA manifestation, and total development to determine possible phases of pathology development. Without the wrist to consider the development of OA the significant coverage on the distal ulna can be only speculated, yet the GIS output offers spatial data to consider and support or refute these possibilities.

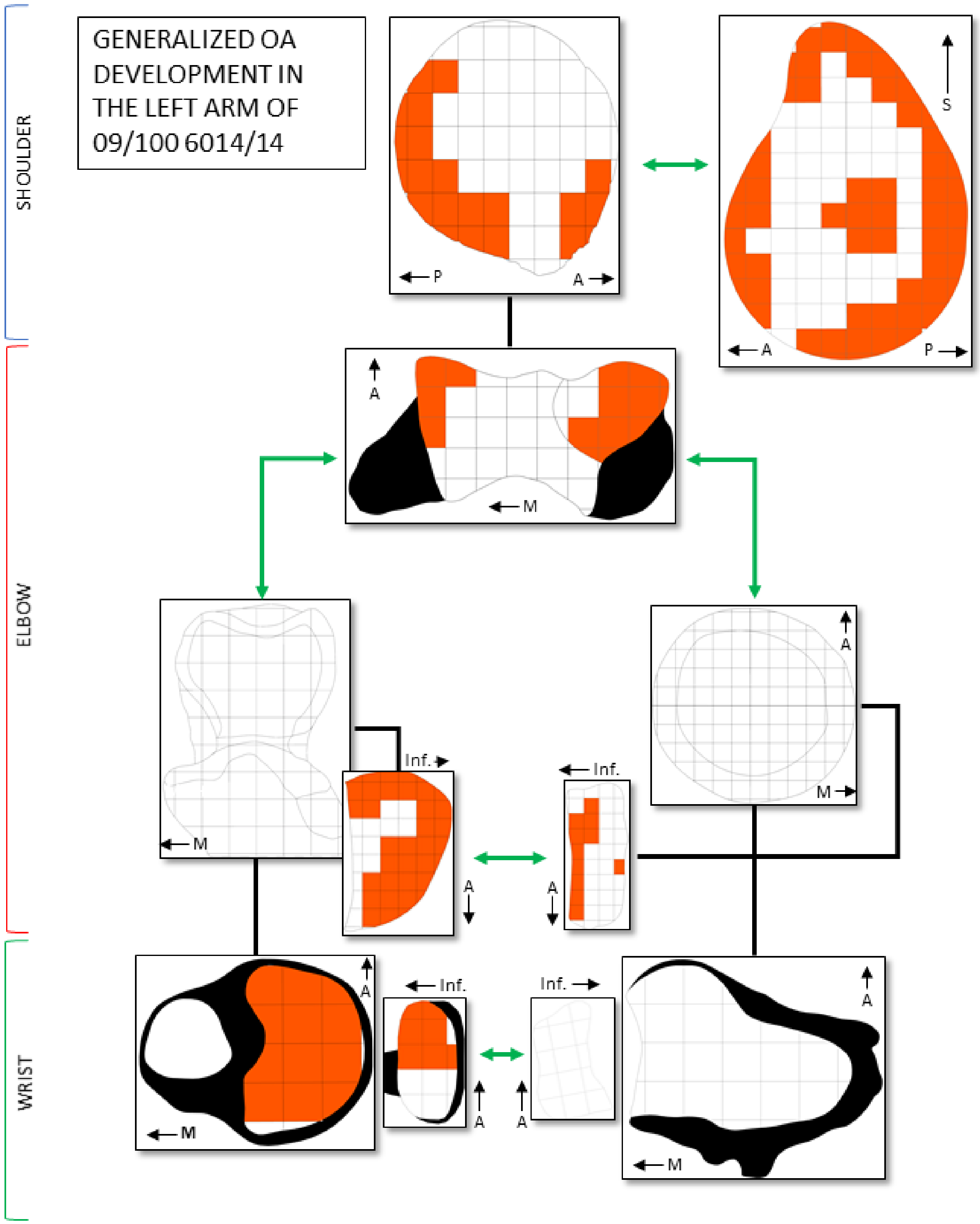


Figure 35: Generalized OA development within the left arm of 09/100 6014/14. Orange areas indicate OA manifestations on the articular surface intersect with the tessellation grids.

V: DISCUSSION AND CONCLUSION

There is a two-sided argument to be made about OA data collection concerning the focus on OA diagnosis versus the understanding of OA progression. One argument involves the diagnosis of OA. Those using methods outlined in Rogers and Waldron (1995) and Waldron (2009) focus on the definitive diagnosis primarily using eburnation, yet a combinations of two other OA characteristics (e.g., marginal osteophytes, pitting, or bone contour change) will suffice for diagnosis. The other argument recognizes our lack of knowledge of the OA pathology and focuses on a broad collection of characteristics to discern their place in the progression of OA as is shown in Buikstra and Ubelaker (1994). It is generally accepted that eburnation indicates a more extreme progression of the disease and therefore the prevalence of the disease would be skewed toward more extreme and possibly late stage cases. Therefore, a wide collection method may be preferable to understand this progression by resulting in a wider prevalence of OA - one that would include less extreme and earlier stages.

Since the progression of OA is poorly understood, identifying it only in its most extreme and progressed forms seems counterproductive. This is not to say that the methods outlined by Rogers and Waldron (1995) lead to incorrect diagnosis. On the contrary, the use of bone-on-bone contact is quite diagnostic of the thinning joint space. However, aspects of OA leading to that point are poorly understood and may entail a wider frame of reference to illuminate. As a result, the use of Buikstra and Ubelaker (1994) as an broader data collection method fit well with the underlying paleopathological goal here - a more complete understanding of the OA pathology. Unfortunately, as outlined in Table 2, discrepancy in data collection methods, OA characteristics, and calculation of prevalence vary considerably among researchers. This has led to comparability issues between studies and the prevention of the construction of a large body of descriptive OA data. The idea that standardization might rectify this problem is easier in concept than in practice.

Standardization implies not only the creation of a universal method, but one that is universally used. In order to accomplish this and maximize the possibility that a method might become standardized, it needs to accommodate all characteristics researchers might gather in OA data collection including all OA characteristics and levels of severity. Unfortunately, this also entails a contribution on the part of the researcher to collect data that may be outside the scope of their research, but may be beneficial to more extensive paleopathological research and comparison in a larger interdisciplinary community. Many caution against this level of detailed raw data that would be accumulated including Bridges (1993) who referred to the amount of data as “unwieldy” and “virtually impossible to interpret” (p.289). Rogers and Waldron (1995) found issue in the use of levels of severity citing that there would not be a high level of concordance between observers.

This research attempts to address this confluence of issues including data management, standardization, detail level, and reevaluation by offering a methodology that merges GIS and the paleopathological goal for a better understanding of OA progression. While this blending of technology and interpretation may offer many practical and theoretical uses, it is not without its own issues and limitations. In the following sections these concepts will be addressed including a critical evaluation of the method, best practices, and limitations and future directions.

Critical Evaluation

In evaluating this methodology, certain functional goals had to be met. Firstly, the methodology had to be able to accommodate for a level of data that would include all OA characteristics and levels of expression, while maintaining or improving the existing levels of detail. Secondly, there had to be sufficient ability to recall, manipulate, and analyze this data. Thirdly, the data needed have the ability to be reevaluated. Lastly, the ease of practical use was considered and evaluated. Many of these goals were met and exceeded, while others may need refinement and further testing.

Data

The criteria for data collection was based on Buikstra and Ubelaker (1994). This method was chosen because it acquired the highest level of detail in OA data collection including lipping, porosity, eburnation, levels of expression, and percentage of surface involvement. Data collected using this criteria exhibits a wider scope and does not prevent or limit the use of methods defined by Rogers and Waldron (1995) or adapted by others (Molnar et al., 2011). If needed, the selection for other diagnostic criteria could be performed using this raw data by querying the SQL database created here rather than omitting characteristics in data collection.

The GIS had no difficulty in accommodating any single piece or combination of OA characteristic or expression data. Through the scaling of the articular surface rasters, the system was able to provide accurate area measurements of OA characteristics on individual aspects of the bone or in combination with other characteristics, including the articular surface. The visual aspect of GIS also allowed the observer to note the exact spatial location or amount of marginal lipping on the surfaces so that the percentages of involvement widely used in Buikstra and

Ubelaker (1994) could be observed in greater detail (Figure 5). This mitigates the concerns for unwieldy data and accommodates the wide scope useful in standardization.

Recall and Analysis

The database application functions of GIS proved to be a reliable vehicle for the recall and statistical analysis of OA data. The fields used in the attribute tables proved suitable for querying multiple variables in various scopes of inquiry (e.g., arms, individuals, and sample) (Table 6 and Figure 21). Statistical analysis functions proved to be adequate on a basic level but due to the near infinite possibilities in data manipulation and spatial analysis offered by tools within GIS and programmable through code, they were not explored fully.

The visual aspects of the GIS proved to be more functional within the confines of an isolated articular surface. Visually and statistically relatable data was able to be extracted from singular digitized images (Figure 18). An attempt was made to organize and relate articular surfaces visually and statistically (refer to Figures 24 and 35), but proved difficult due to scaling differences and the rendering of three-dimensional objects in two-dimensional space. In the end, larger visual representations of the joint and the arm were not rendered in a quick and user-friendly manner but proved cumbersome and involved the export of graphic representations from GIS for reorganization in other graphic applications such as Adobe Illustrator, PowerPoint, and the GNU Image Manipulation Program. The pattern representations in the analysis section were also hindered by this difficulty (Figures 28, 31, and 33). While GIS serves as an excellent medium for storage and rendering of individual elements, much of the visual layout was done externally.

Apart from the difficulties in visual organization, the OA data within GIS provided visual representations of patterns within the pathology. With few exceptions (refer to Angel, 1966; Merbs, 1983), detailed patterns of OA changes are rarely recorded by modern methodologies in favor of prevalence and joints affected. GIS provides visual renderings of the pattern OA involvement in the skeleton which has been argued to be preferable (Lessa, 2013). Chapman and Stewart (2014) demonstrated the utility in using GIS to investigate OA hotspot patterns with a population sample from the Erie County Poorhouse. The analysis focused on the OA 'hotspots' originating within the elbow and knee, yet remained focused on the comparison of patterns, and did not elaborate on the data collection aspects (Chapman and Stewart, 2014). These patterns not only have implications in the interpretation of biomechanical stresses on the bone which can lead to osseous changes (Ruff, Holt, and Trinkaus, 2006), but they also provide a detailed pattern useful for diagnosis and epidemiological comparisons (Dobson and Waldron, 2019; Weiss and Jurmain, 2007).

As an example of this, the models of the left and right elbows of 11/1 5540/13 exhibit patterns open to biomechanical interpretation (Figures 33 and 34). The difference in the areas of OA coverage specifically within the proximal radius and ulna within the left elbow of 11/1 5540/13 in comparison to the right might indicate that the left arm possibly exhibited significantly more stress in the pronation and supination of the forearm. While many of these motions are simplistic in nature, it is important to consider the body in living form produces stress as a product of compound motions. For example, Aguinaldo and Chambers (2009) found a full combination of body motions including step, trunk rotation, and shoulder angle all contribute to valgus torque loading within the ulnohumeral joint – more so than a joint moved in isolation. As a result, patterns should be considered through the evaluation of the entire arm and, if possible, the entire body. Many researchers also find value in highly detailed patterns of OA in archaeological populations as a means to interpret bilateral asymmetry, gendered labor divisions, and epidemiology, while others have adapted their own or argue for a method of recording them (Jurmain, 1990, 1991; Jurmain and Kilgore, 1995; Lessa, 2013; Weiss and Jurmain, 2007). Highly debated among these is the interpretation of patterns in relation to activity. This methodology offers the opportunity to explore this relationship through the pairing of patterns of OA with wider contextual data including ethnographic reference, archaeological data, age, and biological sex (refer to: Merbs, 1983; Schrader, 2012).

If this patterning can aid in determining the relationship among articular surfaces and activity patterns, then this process may also aid in the speculative assessment of articular surfaces destroyed by taphonomic factors through the assessment of the surviving opposing side. For example, individual 11/1 5619/4A is biologically male and has been determined to be of a younger age due to the presence of fusion lines on the epiphyses of all elements within the arm (Willems, 2006). Unless extenuating circumstances are a factor, this individual should not exhibit OA manifestations and, as a result, all articular elements are clear except for the right radial head. The right radial head exhibits an area of increased porosity that could be defined as a bone cyst of unknown origin. Yet, with this area of porosity being as large as it is, an acceptable hypothesis would be that the corresponding joint would exhibit changes as well. The capitulum of the right distal humerus did exhibit these same changes in the area corresponding to the one on the radial head (Figure 36). This could have been anticipated even if the distal humerus was destroyed by placing a mirrored modeled image of the radial head onto the surface of a distal humerus model and extrapolating the corresponding image to the capitulum.

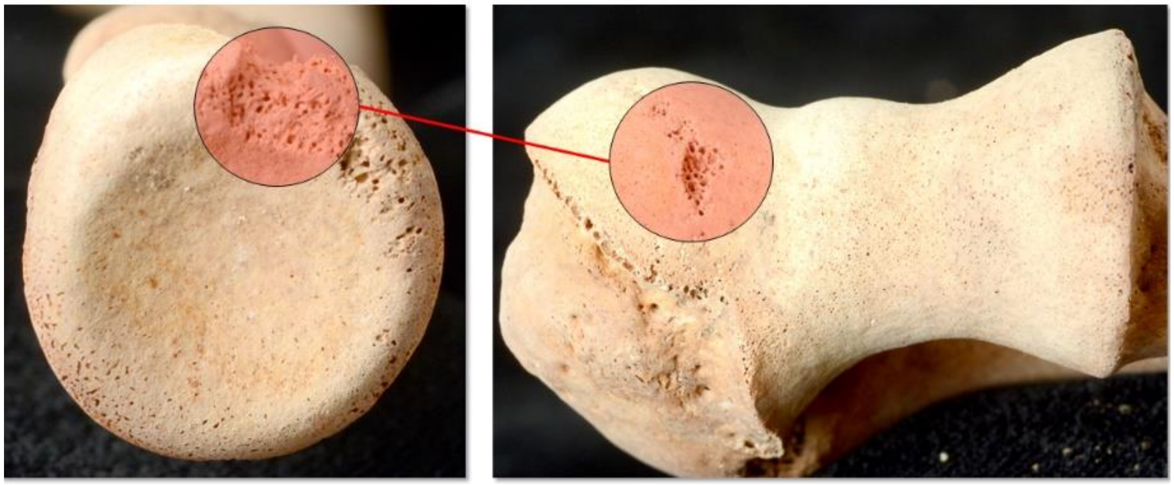


Figure 36: Correlating affected areas of a possible bone cyst in the left elbow of individual 11/1 5619/4A. This comparison illustrates the interactivity between articular surfaces and the possibility of utilizing modeling to see patterns between bones and hypothesize the locations of OA on missing elements.

Complementary patterning may be apparent in OA affected articular surfaces of sufficient expression as well and the use of modeled patterns may offer a means to reveal these. Both the left glenoid and proximal humerus of 09/100 6014/14 show this interaction. Areas of the anterior and posterior humeral head interact with corresponding areas within the arm's range-of-motion on the margins of the left glenoid (Figure 37). Assumptions as to the extent of expression needed to cause a response from the opposing joint surface and the progression thereof would be ideal questions to be evaluated by this methodology.

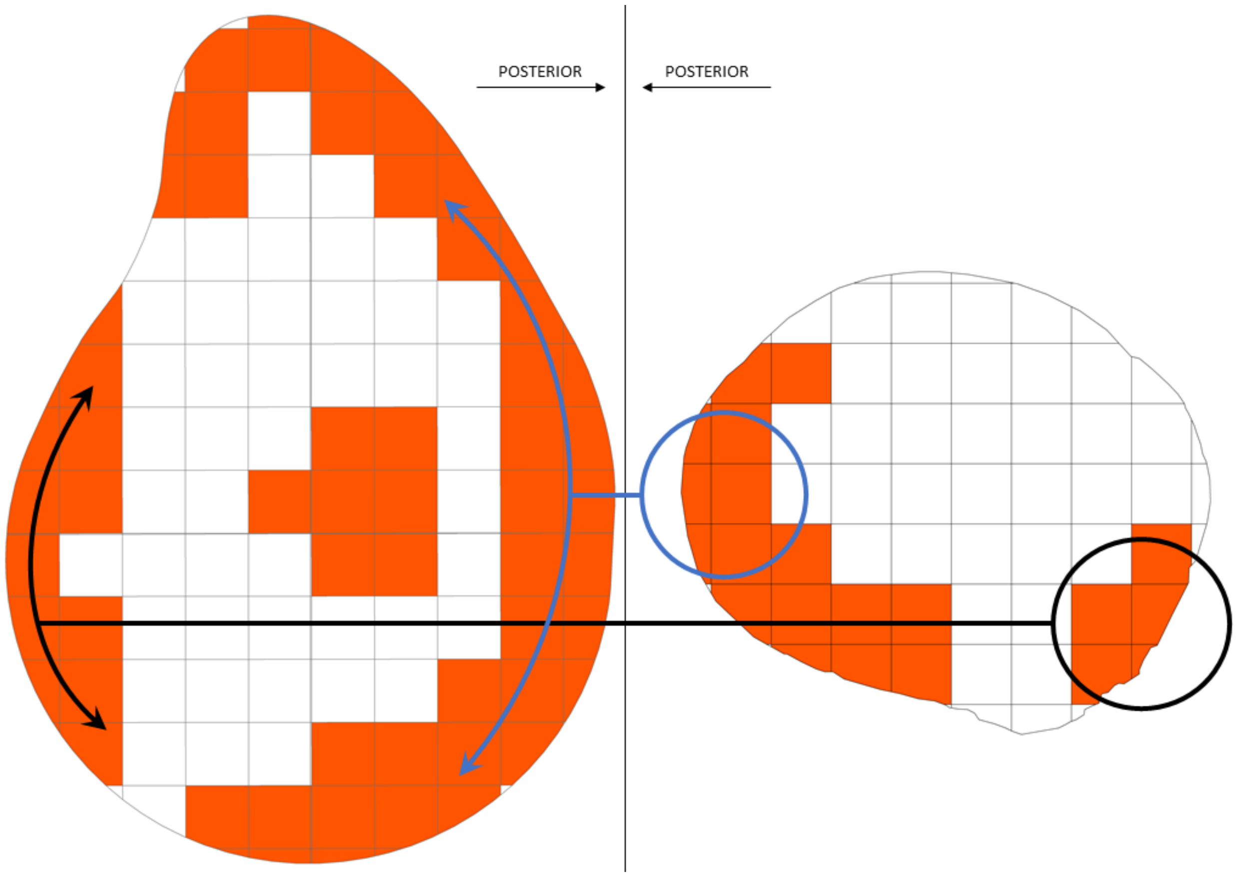


Figure 37: Opposite areas affected by OA within the left shoulder of individual 09/100 6014/14. These areas may indicate patterns of development between opposing surfaces that affect along the range of motion.

Reevaluation

One of the primary concerns about the increased level of detail in OA data collection is that the more intricate the assessment is, the lower the concordance between researchers will be (Rogers and Waldron, 1995). This is an understandable concern because traits delineating the levels of expression are open to a wide interpretation. This can be dependent on experience level in the recognition not only of OA manifestations, but of other similar pathologies that may masquerade as OA. However, these issues and others like it can be mitigated through reevaluation. It is not possible to remove all interobserver variation even within the use of GIS, but the process behind the initial evaluation can be understood though the placement and type of shapefile used during digitization. This explanation into the areas and characteristics of the recording procedure would not be typically available unless the original recorder or detailed raw data was present. Elements such as the extent of surface affected, type of OA characteristic, and level of expression, are able to be understood, if needed, refined. While this still allows for variation in the prevalence of OA severity within samples, it narrows the scope of this variation to less than what would be expected with variations in OA diagnostic characteristics. It is plausible that through the ability to reassess the articular surface, variations in recording may become more uniform over time through debate and discussion.

The extent of the articular surface is another surprising variable that is able to be reevaluated and may affect the extent of OA data collection. Osteoarthritis characteristics entail the modification of the articular surface to better accommodate the stress being placed upon it. As a result, there can be a wide-ranging variety as to what extent beyond the typically smoother articular surface should be recorded. Should an OA characteristic that extends beyond the nominal joint surface be recognized as an articular surface? The extent of the articular surface often delineates the extent of recording as well. If this number is being used to figure out the percentage of involvement on a surface then the discrepancies can be significant. Consider two hypothetical independent evaluations of the distal end of the left radius. Researcher A shows the extent of the articular surface in light blue while Researcher B also recognizes this as the extent of the articular surface, but acknowledges that there are OA related changes beyond the standard articulation surface (Figure 38). This methodology acknowledges this variation in recording, as well as those in the type and expression of OA. It is the ability to view these recorded areas by additional researches that allows for refinement and reevaluation to take place and by doing so accommodate for variations in recording and analysis.

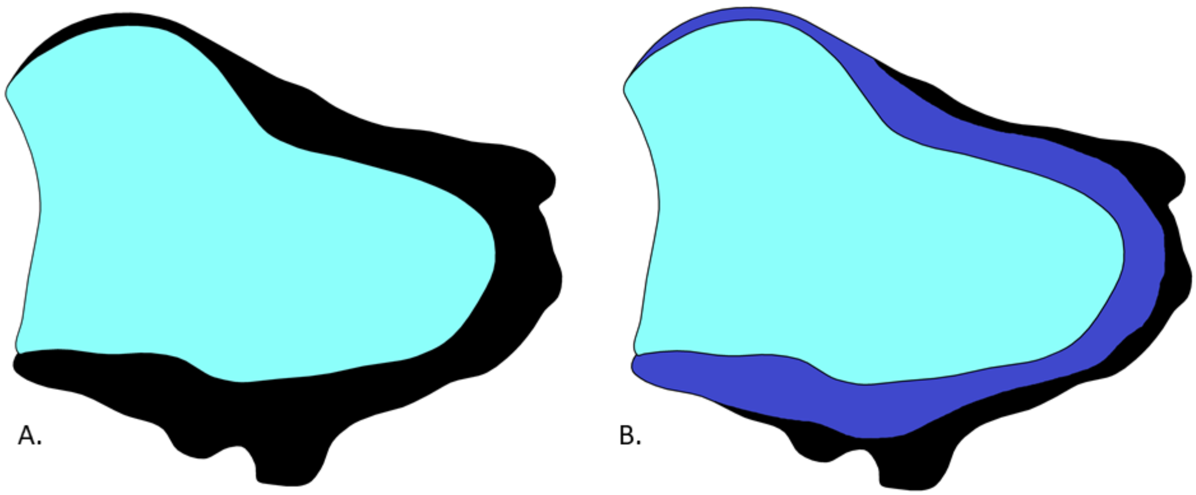


Figure 38: Two hypothetical interpretations of the articular surface extent of the distal left radius.The first researcher (A) records only the changes within the articular surface. The second researcher (B) acknowledges additional changes beyond this extent (dark blue).

Another aspect of reevaluation is the ability to retrieve data from lost sources. The implementation of NAGPRA in 1990 initiated the long-awaited repatriation of many Native American skeletal collections and what scientists would see as a loss of data (Buikstra and Ubelaker, 1994). Because this methodology utilizes standard field photography techniques, archival photographs of remains with OA that have been reburied are able to be documented in GIS – providing a clear depiction of the articular surface and a scale is in the photo. This would enable researchers to acquire new data and pattern analysis from remains that have become repatriated and exist as no more than archival photographs.

Practicality

It is the intent of this methodology to increase the resolution and density of the data being collected for OA in dry bones; however, widespread usefulness of a methodology depends on the acquisition of the components needed to implement it and, above all, how much time it takes to understand and execute it. The GIS portion of this methodology was created with a moderate understanding of the software and, as a result, the full array of tools and capabilities within GIS have yet been utilized. Hopefully this method will encourage the acquisition of raw OA data through which additional analysis techniques can build upon at a later time. Considering these factors, the level of the researcher's familiarity or lack of with GIS software should not hinder the usefulness of this method.

However, with the acquisition of high-quality data comes the time it takes to create it. With optimal photography, each arm has approximately 11 separate articular surfaces: glenoid, humeral head, distal humerus, proximal ulna, ulna PRUJ, radial head, radius PRUJ, distal ulna, ulna DRUJ, distal radius, and radius DRUJ. Each of these, even without OA, should be scaled and have the articular surface layer defined. If they have OA characteristics, each of these requires a layer, a Total_OA layer, merged layer, and additional rasters for overlays and analysis. Minimally, an arm without OA characteristics will entail the creation of 33 separate elements with a maximum of about 100 if all characteristics and levels of expression show involvement. This means a severely affected individual can entail the creation of almost 150 to 200 elements in the scaling, digitization, and a limited analysis process. In a larger population of 100 individuals the digitization process could conservatively entail a few thousand and more for entire skeletons.

While this methodology may be refined further in the future in order to limit the time consumption needed to implement, the tradeoff for the level of data able to be stored and shared would contribute much to the understanding of OA. It is worth noting that the entire procedure is based on field photography and, while able to be completed on location, it is not imperative to do so. With more than one researcher, data collection and digitization can be completed jointly and in different locations to minimize time consumption.

Best Practices

In its current form, this methodology is fully functional. However, in the future this method can be modified or expanded upon as a means to streamline the data collection process or include additional variables. Anticipating this progression, minor modifications to the OA to GIS process have been presented in a wider scope including modifications not presented in Figure 11 (Figure 39). This includes additions made to the photography section and the inclusion of both basic and additional attributes shown in Table 6 and Figure 21. Because of the wider focus on the joint and population, these fields can be included in the initial template without default values. These can be filled as needed to mitigate the time it would take to create them later.

Photography in two-dimensions offers its own unique set of limitations for three-dimensional objects and there are gaps in the data that are a result of this. Elements such as the articular circumference of the radial head, distal ulna articular circumference, and humeral head were unable to be photographed in a singular frame due to the nature of their shape and the position of the bone during photography.

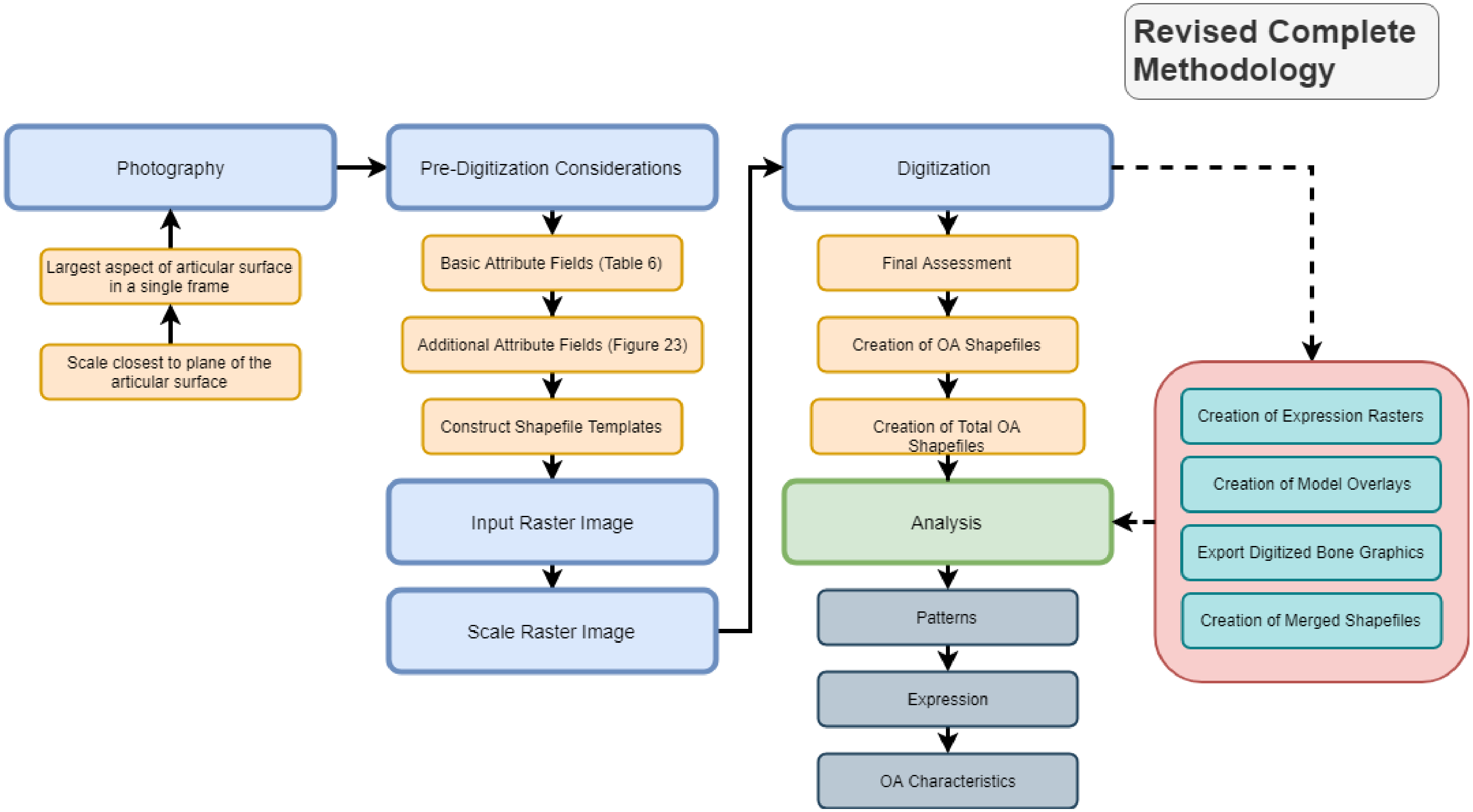


Figure 39: A revised OA into GIS methodology. This incorporates a wider scope than is found in Figure 11 and includes best practices in photography and attribute fields.

This introduced a unique problem in the ‘realistic’ data. Realistic being defined here as the scaled articular surface rasters with the digitized OA types overlaid on top. The problem entailed using multiple photographs to construct a singular articular surface. Due to the curvature of the surfaces, lighting, lack of defined landmarks, and a black background, the ability for software to merge multiple photos of certain elements into a single frame was hindered. If this was the case, often the largest aspect of the element that was shown in a single photograph was used. Future recording should take this into account and provide landmarks on the bones surface to better facilitate photo meshing. This could also be overcome with three-dimensional scanning. However, because the creation of models with tessellation overlays generalizes the location (Figures 33 and 34), it is possible to manually construct these through observation and estimation in order to generalize the pattern on the bone. As a result, these are not affected by multiple photographs.

This issue was especially apparent in the proximal humerus where the rounded humeral head exists partially within five different anatomical positions and as a result, partially in five different images. The humeral head is oriented medially with a slight superior-posterior inclination. Photography in standard anatomical positions cannot capture this completely yet photography at a specific angle is capable of capturing the humeral head in a singular frame. With this maximum view of the articular surface taken in line with the central aspect of the humeral head, scaling and digitization can be completed (Figure 40).

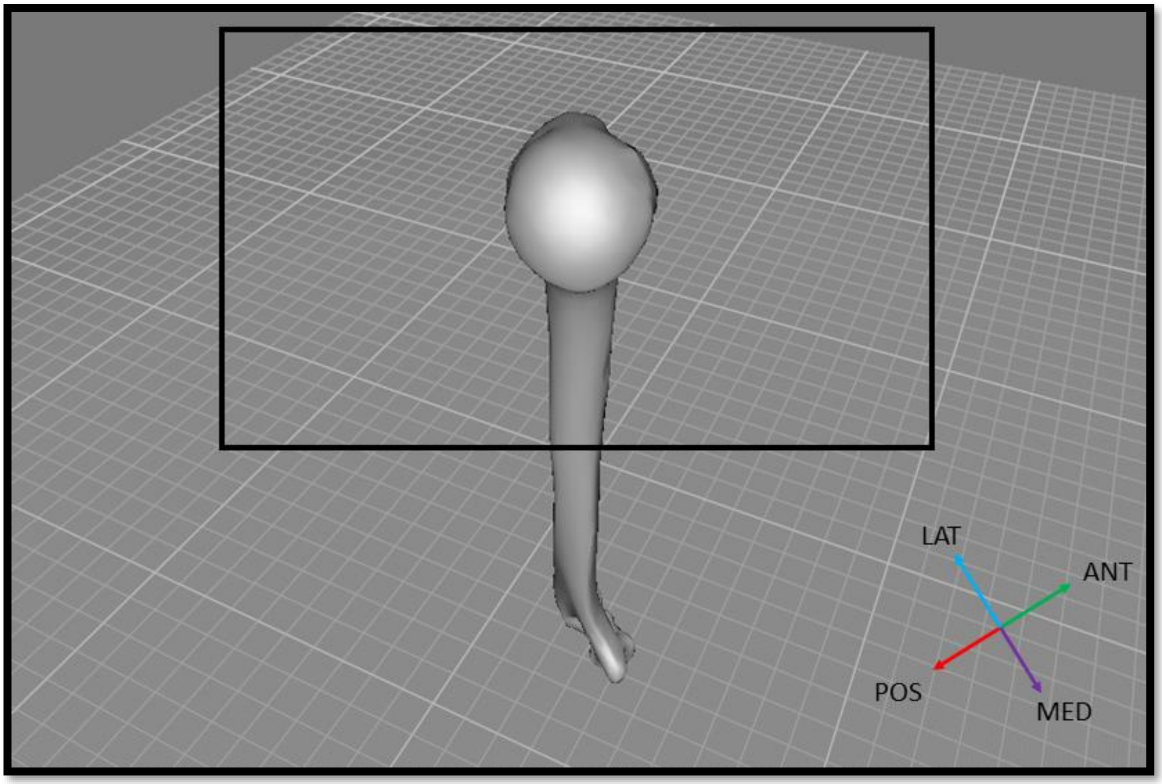


Figure 40: A model of the left humerus showing the positioning and framing for photography of the humeral head. (3D model obtained from BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan).

In relation to the photography, proper scaling of the photo improves accuracy in deriving measurements from the raster image. To improve this accuracy when taking the photographs, the measurement scale should be as close to the plane of the articular surface being digitized as possible in order to minimize error due to perspective distortion. This takes into account that a scale seen at a further distance is smaller than a scale placed in the foreground. If the scale is placed in the background at a distance not within the plane of the articular surface, then this discrepancy will be reflected in picture grid that will be created for georeferencing the raster and likewise the measurements. When possible, both a vertical and horizontal scale should be utilized within the plane of the articular surface. It has been noted that arbitrary measurements of blurred or difficult to view centimeter grids in the photographs contribute to variation within the creation of the picture grid. A dual grid within the plane of the articular surface would enable a more accurate grid construction and likewise, improved accuracy in measurement.

Because of the variations within the human skeleton, any analysis involving the creation of model outlines should be done after the digitization process. This allows for accurate measurements of the bone surfaces so that custom models can be created with an increased opportunity to correctly overlay. This was completed by taking the mean measurements of specific extreme points on the bone surface and then using the measurement and drawing capabilities of GIS to create polyline shapes relating to these measurements. The outcome of this structure was then placed over a photograph of the corresponding articular surface where details of the element's outer structure were outlined to complete the model (Figure 38A). Rather than complete this process for both sides of each bone, the 'Mirror Features Tool' was used in the Editor toolbar. This allowed the model to be duplicated along a defined midline axis. As a result of this custom creation, these models may not be effective to accommodate for all variations in other sample populations.

Limitations and Future Directions

This research does not focus on the diagnosis of OA. It focuses on collecting all accepted characteristics of the pathology including lipping, porosity, eburnation, and their levels of expression. This wide collection protocol aims to provide information on the progression of the disease that remains hidden due to prevalence being selected for by more advanced stage characteristics such as eburnation. A diagnostic characteristic that selects for extreme cases of the pathology may not considerably aid in its understanding through the exclusion of lesser forms. By selecting for these lesser characteristics, it is plausible that in the future certain diagnostic variables in OA diagnosis in dry bone may be eliminated due to a better understanding of this progression.

Unfortunately, this wide criterion can have its own drawbacks. For example, individuals exhibiting porosity at a level 2 expression without any additional characteristics would be diagnostically eligible for inclusion using the criteria in this method. This can result in what is known as over diagnosis, or the inclusion of individuals who have similar pathologies that may not be OA. It is expected that non-fragmentary collections would exhibit a lesser occurrence of over diagnosis due to the diagnostic characteristics provided by the rest of the skeleton. However, in fragmentary collections over diagnosis a possibility but because of the more common nature of OA, may occur less than expected.

In the development of this research, the sample population was utilized to show the proof-of-concept and display possible avenues for analysis based on hypothetical research questions. It is the purpose of this research to provide increased detail in the OA data gathering process and to provide examples of analysis potential through GIS. Data provided by this analysis may serve to provide clues as to biomechanical stress acting upon the an individual or the population, or may provide evidence of OA development and progression throughout the arm. Ten individuals' arm articulations were completely digitized and placed in a queryable database, yet only select individuals were used to show analysis concepts in Chapter IV. This information is presented as raw data and proof-of-concept analysis. No direct interpretations of this sample have been made beyond theoretical speculation toward future research. Future analysis will entail the use of a larger population sample to determine the potential of this method before being applied to analyze an archaeological population. Further exploration into the analysis capabilities of GIS is also anticipated including the feasibility of using Nearest Neighbor Analysis to determine clustering or dispersal of OA characteristics.

The concepts outlined in this methodology are performed in a two-dimensional space. While this may still demonstrate improved accuracy over existing methodologies, the technology has improved to allow three-dimensional scanning and photogrammetry. The ArcGIS 3D Analyst extension provides the means to import three-dimensional meshes as a multipatch feature into the database. This movement toward three-dimensional models would eliminate difficulties in integrating articular surfaces, relating spatial relationships between elements, and add additional depth (e.g. humeral head or femoral head) into the GIS. This is a logical step in the progression of a more accurate methodology. While the application for GIS to perform layering tasks in three-dimensions is still limited, it shows potential to develop as 3D scanning techniques become more mainstream. In its present state, it may be particularly functional in the spinal column where most articular facets are flat, easily photographed, susceptible to OA, and easily layered. Regardless of this possibility, the method as it is now should be utilized on a larger population to test some of the possibilities that are touched upon in this research.

Conclusion

Considering Ortner's (1991) placement of methodology on the stages of development for paleopathological research, the method for initiating research should be considered with great care. The method should reflect the area of interest and also relate to the collection of descriptive data as a means to accomplish this goal (Figure 1). If the area of interest is a better understanding of OA progression from its earliest possible inception, then optimally the following should be encouraged. Firstly, the data collected should be easily comparable. This can be accomplished though standardized methodologies. Secondly, the data should not skew toward a specific point of development of the pathology. This can be accomplished through a wide data collection protocol which can provide developmental and progression data of the pathology.

The variation in the process for calculation of OA prevalence stems from the use of different methodologies which employ different combinations of OA characteristics and levels of expression to determine prevalence. Unfortunately, the focus on eburnation in this process has placed the focus on more developed cases rather than emerging ones. This concentration on a definitive diagnosis has left gaps in what could be OA development and progression data while the difference in calculated prevalence has left studies difficult to compare.

Even in the abbreviated form shown in this work, this methodology has demonstrated that GIS is capable of recording and manipulating dense amounts of raw OA data in all its characteristic forms and expressions allowing for larger datasets and ease of comparison between datasets. It has also shown that these OA characteristics and expressions can be queried and provide spatial patterns originating in the arm. Through the ability to analyze data and render spatial patterns of OA, this method has the potential to show a wider scope of OA pathology progression and its relationship to biomechanical influences.

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